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A numerical investigation of performance and optimization trends of direct contact heat exchangers

Richard Arlen Brickman
University of Nevada, Las Vegas

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UMI

A NUMERICAL INVESTIGATION OF PERFORMANCE

AND OPTIMIZATION TRENDS OF DIRECT

CONTACT HEAT EXCHANGERS

by

Richard A. Brickman

A dissertation submitted in partial fulfillment
of the requirements for the degree of

Doctor of Philosophy

in

Engineering

Mechanical Engineering Department
University of Nevada, Las Vegas
December 1996

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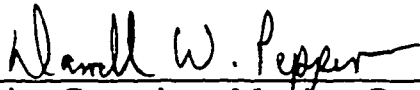
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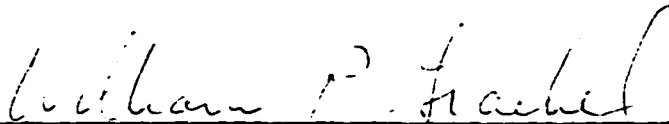
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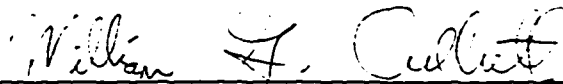
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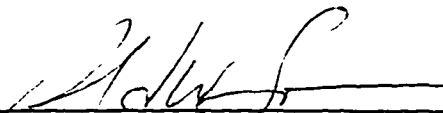
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Graduate Faculty Representative, William C. Culbreth, Ph.D.

Dean of the Graduate College, Ronald W. Smith, Ph.D.

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ABSTRACT

A numerical model has been developed that can be used for industrial

design of a wide range of direct contact heat exchangers (DCHXs). This model is

built from some earlier work where a one-dimensional model was used to describe

some very specific and limited DCHX spray-column configurations. Changes to

the initial model are proposed to reflect more accurately the physics of the flows

found in both two- and three-phase DCHXs. In addition, generalizations are

incorporated into the model to be able to analyze a wide variety of fluid

combinations and roles (either as the dispersed flow or as the continuous fluid). A

major effort is directed to the development of an optimization that can handle the

complete variety of fluids and configurations for spray columns. Parametric

evaluations are then performed to demonstrate that the model does indeed

perform appropriately, and comparisons are made to existing experimental data.

Finally, an extension to a more complicated configuration is made where the two-

dimensional effects of a sieve-tray-tower exchanger are incorporated. This latter

aspect is the first step in developing multidimensional models.

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NOMENCLATURE

A Column cross sectional area, m^2.

A_B Surface area of droplet/bubble, m^2.

a_b Acceleration of droplet/bubble, m/s^2.

C_D Drag coefficient.

c_p Specific heat, J/kgK.

D Diffusion coefficient, .

D An averaged droplet diameter, $(4R^2+4R_0^2)/8RR_0$, m.

E Eccentricity of vapor cap of droplet undergoing phase change.

g Acceleration of gravity, m/s^2.

Gr Grashoff number.

H Ratio of convective to conduction coefficients, h/k, m^{-1}.

h Convective heat transfer coefficient, W/m^2K, or step size.

I Number of nodes in x direction in two dimensional analysis.

i Enthalpy, J/kg.

J Number of nodes in y direction in two dimensional analysis.

K Indexed parameter used in Runge-Kutta solution

k Conduction coefficient, W/mK.

L Column length, m.

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$LMTD$ Log mean temperature difference, °K.

M Ratio of liquid density to vapor density.

$\bar{M}$ Molecular weight of fluid or gas.

m Mass, kg.

$\dot{m}$ Fluid mass flow rate, kg/sec.

n_B Number of bubbles in control volume.

Nu Nusselt number.

P Pressure, Pa.

Pe Peclect number.

Pr Prandtl number.

$\dot{Q}$ Heat transfer rate or duty, W.

R, r Droplet/bubble radius, m.

Re Reynolds number.

S Reference cross sectional area of droplet/bubble, m^2.

Sc Schmidt number.

Sh Sherwood number

T Fluid temperature, °C.

t Time variable.

U Fluid velocity, m/s.

V Volume (control volume or droplet/bubble), m^3.

w_o Optimized weighting

X, x Fluid quality (0=liquid to 1=vapor) or location in two dimensional analysis.

x

y	Non-specific variable or location in two dimensional analysis.
z	Column location (axial), m.
z_D	Normal distance of droplet rise, $z/2R$.

Greek

α	Thermal diffusivity, $k/\rho c_p$, m^2/s.
β	Droplet half opening angle, radians, or grid aspect ratio.
γ	Constant coefficient of time describing rate of change of temperature of fluid surrounding sphere.
Δ, δ	Difference.
η	Heat loss coefficient, $\dot{Q}_L/\dot{Q}_e$
κ	Parameter used in equation 16 defined in equation 17.
μ	Viscosity, Pa-s.
ν	Kinematic viscosity, m^2/s.
ξ	Parameter used in equation 52 and defined in equation 53.
π	3.141592654
ρ	Density, kg/m^3.
σ	Molecular property used in Chapman-Enskog theory (Cussler, 1984).
ϕ	Holdup ratio (also known as void fraction).
ψ	Stream function.
Ω	Molecular property used in Chapman-Enskog theory (Cussler, 1984).
ω	Vorticity, rad/s.

xi

Subscripts

0	Initial condition.
1	From point of droplet injection or indexing.
2	From point at which bubble completes phase change or indexing.
3	Indexing
4	Indexing
B, b	Droplet/bubble.
C, c	Continuous fluid.
cd	From continuous fluid to dispersed fluid.
D, d	Dispersed fluid.
fg	Fluid to gas state change
FT	According to work by Fan and Tsuchiya (1990).
hc	High circulation regime.
i	Spatial index.
inj	Droplet injection regime.
j	Spatial index.
JS	According to work by Sideman (1966) cited by Jacobs(1988).
k	Step index
max	Maximum.
n	Time step index.
o	Outside (exterior) of droplet/bubble. . . . .
ph	Phase change regime.

S	According to work by Sideman (1964).
sr	Stable rise regime.
STr	According to work by Steinberger and Treybal (1963).
$surf$	At droplet/bubble surface.
T	According to work by Tochtani (1977b).
v	Vapor
vbr	Vapor bubble rise regime.
x	With respect to the x-axis or direction.
y	With respect to the y-axis or direction.
z	With respect to the z-axis or direction

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CHAPTER 1

INTRODUCTION

Direct contact heat exchange is a process that offers a highly efficient means of transferring heat between fluids. It is a process that sees use in chemical, geothermal, and manufacturing engineering, though surprisingly, its use is not wide spread in these industries despite its many commonalities with widely used direct contact mass transfer processes. Current research is equally sparse compared to other conventional forms of heat exchange processes. The reasons for the paucity of current research and use are the general lack of understanding of the direct contact processes and the availability (or absence) of simulation software or codes that can aid in producing useful designs.

As the name implies, a direct contact heat exchanger (DCHX) is a heat exchanger that functions by bringing two *working* fluids - one *continuous* and one *dispersed* - in direct contact with each other. By using this kind of process, convection heat transfer takes place sans the impedance of channel walls or tubing common in other types of heat exchangers. Direct contact processes offer benefits over other conventional types of heat exchangers that include: 1) reduced capital cost due to generally simpler design, 2) higher operating efficiencies due to the elimination of the physical interfacing barriers, 3) the ability to achieve close

1

temperature approaches, and 4) reduced operational maintenance due to the elimination of the fouling problem normally associated with tubes and channels.

Direct contact processes are not without limitations and though relatively few, they include 1) the necessity that the working fluids be at the same pressure, 2) the need for sufficiently differing densities to facilitate proper flow (countercurrent in most cases) and reseparation of the fluids, and 3) the requirement that the fluids be immiscible.

As stated, DCHX processes see selected use in industries and research. A notable example in the area of geothermal power production is the East Mesa heat extraction study (Orlander et al., 1983) conducted on the Salton Sea in southern California. In the East Mesa project, a 10-meter vertical device and supporting facilities were constructed at a geothermally active area of the Salton Sea. Utilizing isobutane and geothermal well brine, a DCHX was operated and monitored to study the efficiency of extracting heat from geothermal wells. Another notable example of direct contact use is a hot water generation application in the U.K. (Baker, 1987) where a DCHX was built and operated at a tannery. The tannery used the system to generate a high volume of hot water needed for the hide tanning process. Exhaust from a combuster resembling a jet engine is forced through a vessel of water, heating the water to a desired temperatures.

By no means a new concept - studies of various aspects of DCHX thermo and hydrodynamic mechanisms date to the 1940s and 1950s - the use of direct

contact heat exchange is not widely employed, despite as stated, its close resemblance to direct-contact mass transfer. Examples like those cited are in fact relatively few. Much of the data and analyses being reported in the literature are derived from laboratory models or experimental prototypes.

One reason for the lack of practical use of this process has been the stated continued lack of understanding and adequate design tools for these systems. In some cases, classical means of calculating performance and efficiency fail to yield meaningful information when applied to direct-contact devices. Further, the thermo and hydrodynamic responses of fluids in direct contact are more complex. Performance evaluation requires detailed knowledge of the convection heat transfer processes associated with droplets and bubbles of one fluid passing through another. The complexity of two and three-phase convective transfer hinders finding simple rules of thumb. Systems that are in use today are generally the result of individual experience or iterative trial and error. There is a need for useable software code capable of simulating the direct-contact exchange processes.

A number of individuals have pursued studies in direct-contact heat exchange and related areas. Several exceptional works are particularly notable. Kreith and Boehm, Direct-Contact Heat Transfer (1988), is a compilation of articles addressing a broad range of issues related to the DCHX design process. A chapter of that text, authored by R. Letan, discusses rules of thumb for achieving DCHX designs. Jacobs (1988) presented a comprehensive treatise of the key mechanisms in DCHX processes.

A number of important works - Sideman (1964, 1966a, 1966b), Tochitani et

al. (1975, 1977a, 1977b), Moresco and Marschall (1979), and Johnson and

Marschall (1985) - have contributed to a better understanding of the various

component processes such as the dynamics of and heat transfer to droplets and

bubbles in various continuous media. A particularly in-depth treatise of the

complex wake dynamics and heat transfer of bubbles is Fan and Tsuchiya, Bubble

Wake Dynamics in Liquids and Liquid-Solid Suspensions (1990). The authors of

this text provide many formulations and relationships, but suggest that much more

work can be done in this complex field.

The purpose of the work herein is to create an integrated model using

results and findings from the literature to simulate the performance of a selected

range of DCHXs. In creating such a model, an economical means will have been

developed that allows previewing DCHX designs and variations prior to actual

construction and experimental testing. With energy use a constant issue in most

industrial endeavors, the need for efficient production, extraction and use will

always remain high. Direct-contact heat exchange is a highly efficient process that

can potentially be used in more and more applications given that a clearer

understanding of the processes can be achieved.

DCHX Systems and Processes

As stated in the opening paragraphs, the direct-contact processes function by bringing two working fluids in direct contact with each other. This is done in a device called the direct-contact heat exchanger. While variations of these devices are many, they generally consist of a vertical chamber or column accessible at both ends through which the fluids are introduced and extracted. The simplest of these devices is the open spray-column shown schematically in Figure 1. In this type of device, a continuous fluid (commonly water or brine) is pumped into the top of the column and allowed to pass unobstructed to the bottom of the column, where it exits from the device. As is often typical (e.g. geothermal applications), the continuous fluid enters at a high temperature and serves to heat a suitably selected dispersed fluid introduced at the bottom of the column. The dispersed fluid, generally of lesser density, rises buoyantly through the column, receiving heat from the continuous fluid until it reaches its exit at the top.

A system is *two-phased* if the continuous and dispersed fluid retain their state throughout the contact. If one fluid (often the dispersed fluid) undergoes phase change, the system becomes *three-phased*. Two-phase systems are further delineated as liquid-liquid, liquid-vapor systems, or (less frequently) liquid-solid systems.

Other types of DCHXs configuration have been developed with the intent of enhancing system performance and/or efficiency. Alternate design enhancements include packed beds, baffles, axial agitators, and sieve trays, to
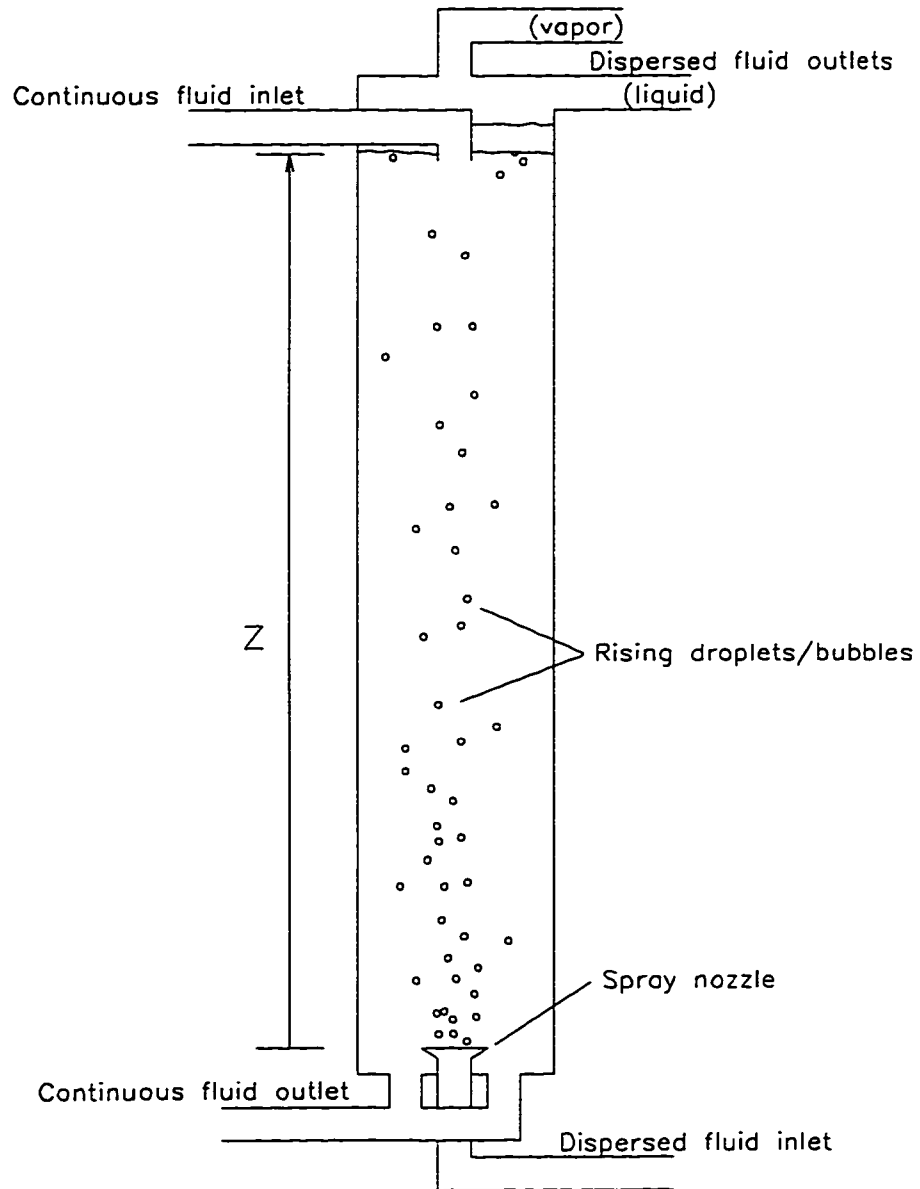
Figure 1 Schematic of Simple Spray-Column Direct-Contact Heat Exchanger (DCHX).

name a few. Each of these variations functions fundamentally the same as the spray-column in that counterflowing fluids are in direct contact. The enhancements are made to improve the heat transfer by creating better convection processes, each having merit to one degree or another.

In constructing a model that simulates the spray-column system, it is important to incorporate as many of the physical mechanisms as possible in as true a form as possible. By doing so, a resulting model has the most chance of working for a wide range of specifications and conditions. Realistically, this is not always possible, given the large numbers of factors influencing performance, but it is what should be strived for.

A number of works have been published on the modelling problem containing an assortment of approaches. Each has merits for the specific applications to which it applies. Some are limited in scope, describing a specific aspect of direct-contact exchange such as flooding (Golafshani and Jacobs, 1989) or droplet rise (Mansson and Marschall, 1994). Yet others provide for modelling of a specific configuration such as liquid-particulate solids (Tadrist et al., 1985) or two-layer melting (Hong and Saito, 1993). More generalized works on spray-column DCHXs have been published by Coban (1986) and Coban and Boehm (1986). Ay et al. (1994) closely followed the Coban and Boehm approach, work which to date is the most universally applicable. A one-dimensional model that models an enhanced version of a DCHX was developed by Summers and Crowe (1991). This work addresses a packed bed system and agrees reasonably with

experimental data. The Coban and Coban and Boehm works comprise a fine attempt at modelling the hydro and thermodynamic responses of a three-phase counterflow direct-contact heat exchanger. The modelling sets down a solution algorithm for the governing one-dimensional differential equations, using a variety of supporting empirical expressions. The heat transfer processes are delineated for two and three-phase systems where liquid droplets or gas bubbles rise through a counterflow continuous fluid. Results of the model are compared (apparently favorably) with experimental data from a laboratory device.

Reconstruction of the Coban model - first by direct transcription of the published code and then by recreating a code from the analysis and algorithms - was undertaken as background for this work. Transcription of the code was unsuccessful. Recreating the code based on the algorithms given led to the discovery of suspected errors in some of the analyses. The apparent agreement between predicted and experimental data appeared to be due to offsetting errors, thus leaving open the need for a generalized model capable of correctly simulating DCHX processes.

The primary physics involved in spray-column DCHXs is the heat transfer to and from droplets and bubbles rising through a counterflowing medium. From injection to exit, a dispersed fluid can pass through six separate regimes. The six regimes are divided between the liquid and vapor phases of a typical three-phase system. These regimes - represented in Figure 2 - are *droplet injection, high circulation,* and *stable rise* for liquid droplets and *onset of phase change, two-phase*

rise, and vapor bubble rise for vapor bubbles.

The *droplet injection* regime is characterized by rapid droplet growth and internal fluid circulation. It is found that convection heat transfer is high due to the internal circulation. Depending on the injection flow rate, orifice size, fluid properties, etc., a droplet being released from a nozzle takes on a myriad of elongated shapes until it separates. Time spent in this regime is very brief.

The *high circulation* regime begins at the point a droplet separates from a nozzle port. As the name implies, it is initially characterized by high internal droplet circulation. Droplets in this regime, however, also see a decay of the circulation as internal viscous forces dampen fluid motion. Time spent in this regime is also brief, lasting only ten to twenty droplet diameters. Droplet shapes continues to oscillate, elongating and flattening.

Culbreth (1983) and Johnson (1985) have studied and photographed the behavior of the first two regimes in simple water-oil experimental systems. Culbreth and Marschall observed that a significant amount of heat transfer occurs within the first ten droplet diameters after injection. This is an important point. Modelling works to date have not accounted for high circulation at or near injection, perhaps due to the brevity of these regimes. Droplets have, instead, been treated as stable, well-formed spheres during their traverse of the DCHX. Jacobs cited several works addressing heat transfer of circulating droplets.

The *stable rise* regime is that portion of the liquid droplets' travel in which the most time is spent. It is a condition that contrasts sharply with the injection

regimes in that the droplet's oscillating shape dampens, taking on a constant spherical shape. Further, internal circulation has also decayed completely. A droplet remains in this regime until onset of vaporization in the case of a three-phase system or until it exits the exchanger in the case of a two-phase one. In a three-phase system, this regime, when combined with the injection and high circulation regimes, is considered the pre-heating portion of a DCHX.

Heat transfer to a droplet during stable rise differs dramatically from the highly circulating conditions preceding it. Heat transfer to a non-circulating droplet is dominated by the internal resistance to transfer, with the droplet taking on the thermal characteristics of a solid sphere. Construction of a heat transfer expression must account for both the exterior convection and internal resistance. In this case a series resistance is formulated. Sideman et al. (1964, 1966a, 1966b) studied heat transfer of stable droplets rising in a continuous medium. Tochitani et al. (1975, 1977b) studied the exterior convection of droplets of varying qualities. Expressions provided by both sources are used in this work.

Onset of phase-change begins at the end of the preheating of the dispersed fluid and like injection, is a brief regime. Here, very little literature material is available. It reasons that there is an increase in internal circulation due to the rapidly changing droplet/bubble shape. Typically the vaporized fluid collects in the upper portion of the droplet/bubble entity, forcing the liquid portion into a cup like shell. The change in shape is rapid, due to the extreme differences in densities. A droplet quality (mass) change of only a few percent can result in an

order of magnitude change in volume. The heat transfer at this stage jumps, resembling that of the injection and circulation.

The *two-phase rise* regime is where a bulk of the overall heat transfer occurs in a three-phase system. This is due to high individual droplet heat transfer as a result of both circulation and the shifting of the droplet's shape from spherical to shell-like. The change in liquid to a shell eliminates much of the internal resistance, allowing the higher external convection to dominate the heat transfer process. Further, there is a high amount of absorption of the transferred heat by the vaporization process, which holds the dispersed fluid's temperature constant during this regime. Tochitani et al. (1977a, 1977b) studied the two-phase rise regime experimentally for a water/n-pentane system and offered expressions for the heat transfer and hydrodynamic motion for qualities up to approximately 0.5. At this point, the upper half of a droplet/bubble appears to be predominantly a vapor bubble having some degree of circulation. Recent work by Fan and Tsuchiya (1990) addresses vapor bubbles of varying shapes in diverse conditions, focusing on the mass transfer characteristics. An analogy is made between mass and heat transfer which provides a means of deriving expressions for use in modelling the heat transfer in this regime.

The final regime is the *vapor bubble rise*. Once again, little is found in the literature about the transition. Coban viewed the vapor bubble as being similar to stable liquid droplet with high internal resistance. Due to the generally low viscosities associated with gases, it is more likely that the bubble interior is

circulating. Better heat transfer expressions for vapor bubbles - making use of the

heat transfer/mass transfer analogy - are found in the Fan and Tsuchiya work.
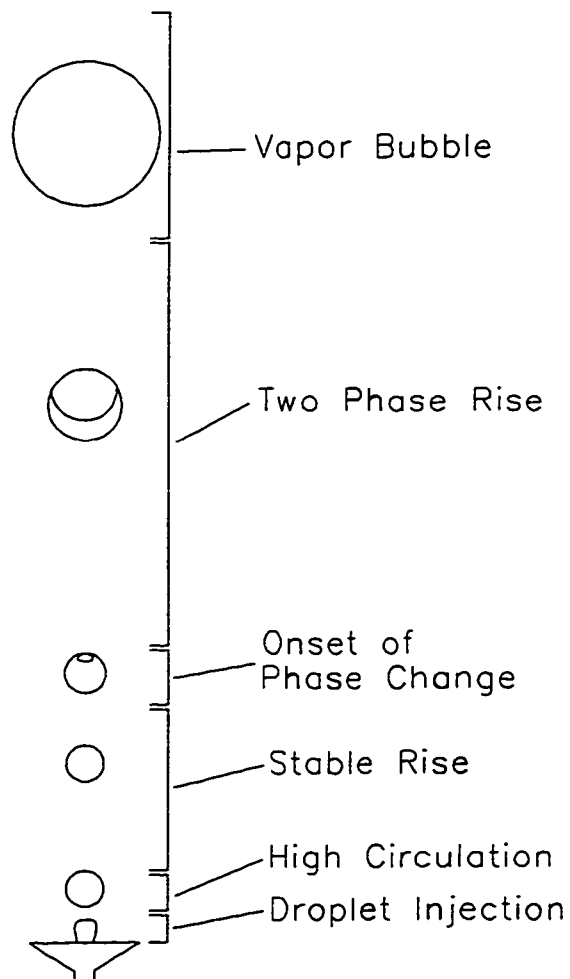
Figure 2 Droplet/Bubble Regimes Occurring in a
Three-Phase Spray-Column DCHX.

The task of assembling a DCHX model is primarily one of assembling a matrix of expressions that describe the heat transfer for each of the regimes which can be used by an algorithm for solving the governing differential equations. Such a matrix must be constructed from available expressions reported in the literature. The selections and detailed discussion of the expressions used in this work are outlined in Chapter 2.

Dual Utility Optimization

Optimization of DCHX systems can be approached in several different ways depending on the type of outcome desired. One of the features of heat exchangers in general - direct-contact included - is the flexibility of their use. One of the uses is maximum heat extraction/addition to a working fluid. For this type of application, one might assume that an abundant amount of a source fluid is available and is used to extract or add as much heat as possible to a target fluid of limited supply. The resulting temperature profile might appear like the hypothetical case shown in Figure 3. An abundant low temperature continuous fluid (perhaps water) is supplied to the top of a DCHX to cool a high temperature dispersed fluid (perhaps oil from some application). The continuous fluid undergoes little change in temperature while the dispersed fluid experiences a wide temperature change. The criteria by which this type of system is considered optimized might be the point at which no appreciable improvement is made in the dispersed fluids temperature excursion, despite the continued increase in the continuous fluid's flow.

A second use of DCHXs is the specific control of a target fluid's temperature. In an application of this type, a DCHX is used to heat or cool a fluid to a specific temperature. This requires adding or extracting heat at a specific rate and presents more challenge since any one of a number of factors can affect DCHX transfer. A profile for this scenario might look like that shown in Figure 4, where the dispersed fluid might enter the system at a high temperature and must exit at a specific level. The continuous fluid's flow rate and inlet temperature are key factors affecting the outcome of the system as are other basic parameters such as device length, dispersed droplet size, operating pressure, etc. A parameter by parameter analysis would be required to determine the right combination of parameters needed to achieve the target exit temperature.

A third distinct use of a DCHX is the transfer of heat in such a manner as to utilize both fluids to the maximum extent possible. This might be desirable when both fluids are of limited supply or the cost of pumping the fluid to and/or through a system is significant. If achieved, a system can be said to have *dual utility optimization*. A characteristic of the fluids' temperature profiles for this type of optimization would be that they undergo equal excursions (are parallel) and that they have as close of an approach as possible. The primary factors affecting a successful balance of parameters are individual flow rates and specific heats.

Figure 5 depicts two cases of dual utilization profiles. In Case 1 (dashed lines), two fluids are input at rates that result in each having the same change in temperature from input to output. However, the approach of temperatures is not

good and although both fluids are undergoing equal temperature excursions, the system is not optimized under the criteria stated for dual utility. Case 2 (solid lines) depicts a second set of conditions that does result in both equal excursions and a much improved, if not maximized, approach of temperatures. (It is noted that the ideal case of the temperature profiles lying on top of each other is not possible since there would be no temperature differential to create heat transfer.) Case 2 qualifies as being optimized for dual utility. It is the dual utility application that is the focus of the optimization analysis in this work.
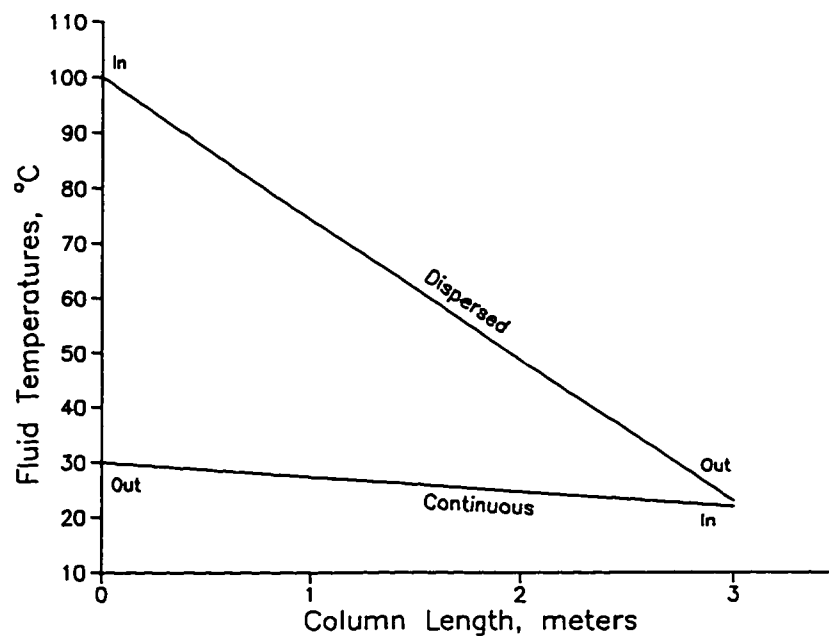
Figure 3 Example Temperature Profile of a DCHX Optimized for Maximum Heat Exchange.
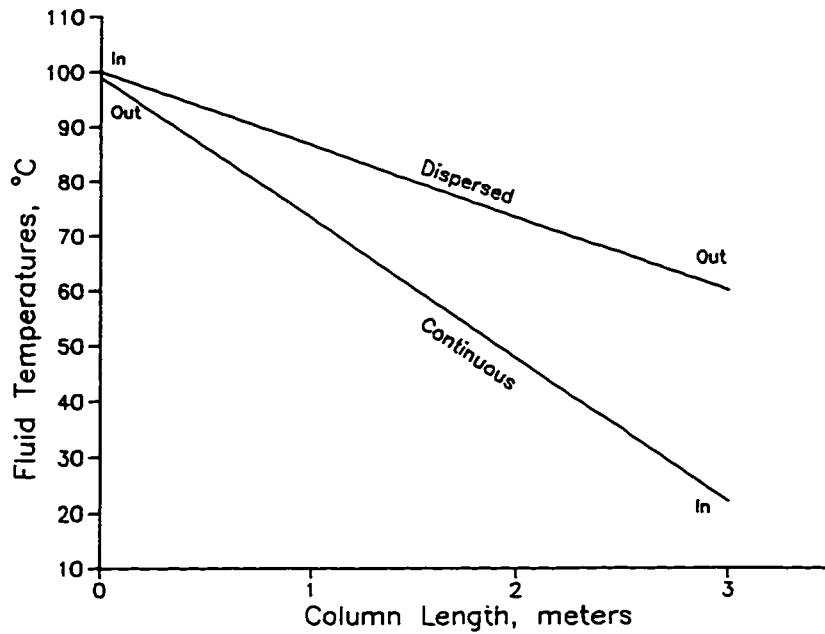
Figure 4 Example Temperature Profile of a DCHX Optimized for Specific Target Temperatures.
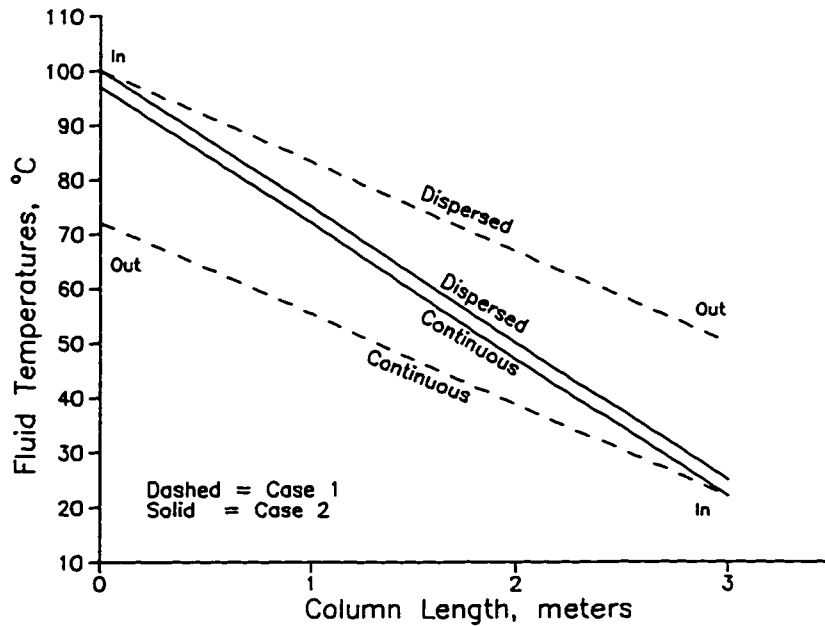
Figure 5 Example Temperature Profiles of a DCHX Optimized for Dual Utility. (Dashed Lines = Partially Optimized, Solid Lines = Optimized.)

A need then arises for an indicator that measures the conditions - parallel and close approach of the temperature profiles - and determines dual utility optimization. Classical expressions such as effectiveness and log mean temperature difference (LMTD) are not useful in providing a measure for this type of outcome. LMTD is of some value in indicating closeness of approach. The lower the value, the smaller (closer) the *average* temperature difference is. However, it does not provide any information as to the parallelism exhibited by the profiles. Effectiveness, as classically defined, offers insight into the system's efficiency and might be of use in determining maximum performance as a trade off to some parameter. A new indicator is therefore needed and developed in this work.

The indicator, referred to as the Dual Utility Optimization (DUO) characteristic, combines a measure of profile parallelism and closeness of approach into a single expression that ranges between 0 and 1. Values approaching 0 indicate poor utilization, and values approaching 1 indicate high utilization noting that the extreme cases - values *equal* to 1 - are not possible as this situation would indicate coincidental profiles, a condition precluded by the physics of heat transfer. The development of the characteristic is discussed in Chapter 2 and results presented in Chapter 3. The indicator is especially beneficial in that it is a well-behaved and stand alone indicator for comparing a wide variety of parameter combinations.

Sieve Tray Enhancement of DCHXs: Two-Dimensional Analysis

It has been found that DCHX output can be measurably enhanced by the adaptation of a spray-column into one of several alternate types of DCHX devices. These adaptations include the addition of packing materials, sieve trays, or column agitators, to name a few. In all cases, fluid flow is altered in such a way that heat transfer is increased. The mechanism responsible for the increase varies from adaptation to adaptation, and it is not completely known what specifically about the altered flows causes the enhanced output, though it is shown that increased convection is generally a greater factor than residence time. In a packed column, hundreds of irregularly shaped objects are randomly packed within the counterflow column, inhibiting the free rise of droplets and bubbles. Droplets continuously collide with the objects and must pass to either side as they restart their rise. It is believed that this slows the rise, thus increasing the droplet/bubble residence time. A second belief is that the continual colliding with the packing objects creates high circulation and strips off unwanted wake, which leads to axial mixing (Kehat, 1971, Letan, 1965).

A second type of enhancement is the addition of a series of partially spanning alternating sieve trays throughout the column. The sieve trays force the continuous fluid to snake back and forth along the length of the column. As a result of this motion, cross flows are set up. Droplets of dispersed fluid are swept left and right as they travel the length of the column. The heat transfer enhancement mechanism is believed to be several fold. First, there is a higher
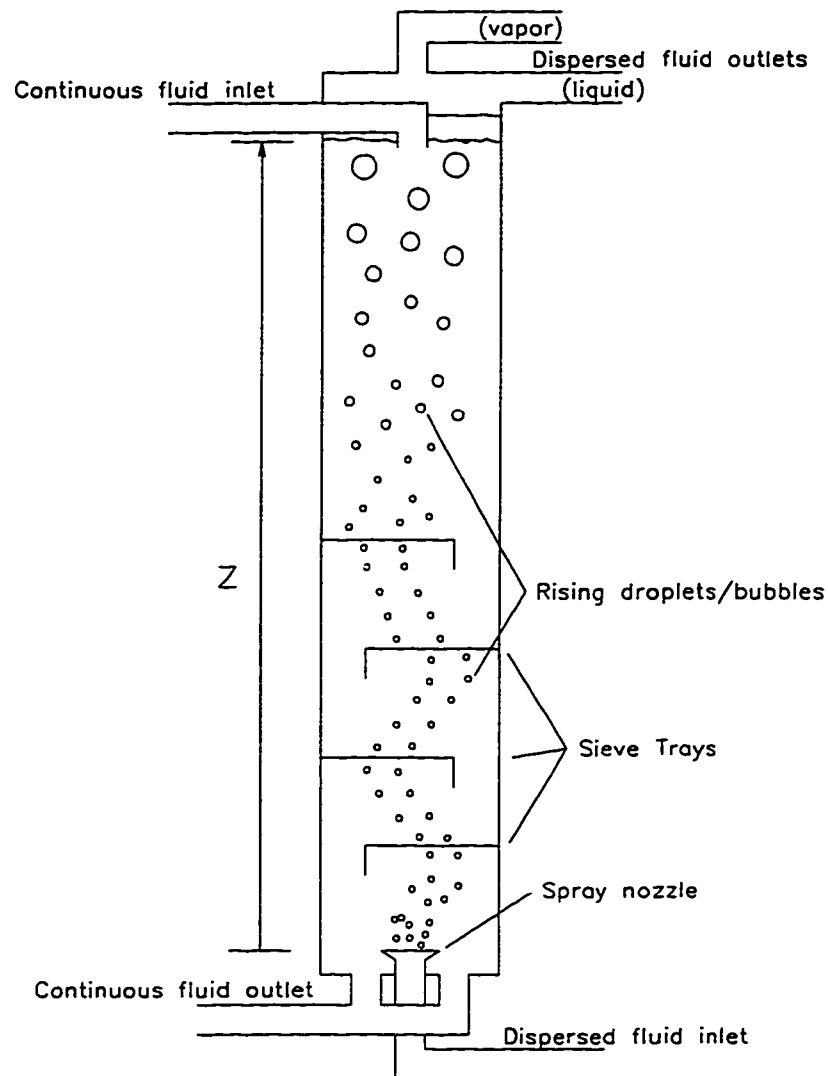
Figure 6 Schematic of Sieve-Tray Enhanced Direct-Contact Heat Exchanger.

relative velocity since the droplets now have a two component velocity vector.

Second, the droplets' size, circulation and wake effects are reset each time the dispersed fluid passes through the perforations of successive trays. Experimental tests by Mines (1983) and Jacobs (1985) have shown gains in efficiency and output by the use of trays.

It would be desirable to investigate which mechanisms are responsible for enhancing performance. To accomplish this, multi-dimensional modelling is needed. The sieve-tray enhancement is a likely candidate for study in that it can be viewed from a two-dimensional perspective. Since sieve-tray design is basically modular (stacked trays), a single module is readily adapted to two-dimensional modeling. Ultimately, the goal is to create a two-dimensional mapping of the flow for analysis. With this mapping, droplet dynamics and thermal response are studied and compared to unenhanced DCHX cases. It is shown that there is an increase in efficiency in heating (preheating) dispersed liquid droplets.

Modelling can be done by using a commercial fluid dynamics code or a written routine. Any identified influences can then be incorporated back into the one-dimensional model and compared to experimental results. Two-dimensional modelling of DCHXs is not known to have been accomplished by anyone to date. Since results can lead to valuable insights, it is a logical step in the investigation into the sieve-tray effect.

CHAPTER 2

MODELLING DEVELOPMENT AND BACKGROUND

A simulation of the one-dimensional (axial) heat transfer occurring between

a dispersed and continuous fluid in a DCHX device requires a numerical

modelling of governing and supporting equations describing the hydrodynamic and

thermodynamic mechanisms. In this work, both a one-dimensional and a

simplified two-dimensional model are developed and discussed. In addition, a new

indicator for evaluating one particular case of optimization is presented, and its

merit is shown.

One-Dimensional Model

The one-dimensional (axial) model serves as the principle tool for the work

studied. It is based on a governing system of ordinary differential equations

(ODEs) describing the physics of one-dimensional momentum and energy transfer.

A set of supporting expressions is included to determine the varicus components

comprising the ODEs. The model simulates a spray-column DCHX which consists

of a vertical tube through which two working fluids pass in counterflow: the

heavier introduced at the top and the lighter at the bottom. The dispersed fluid -

generally the fluid with the smaller flow rate - is introduced into the continuous

fluid through a spray nozzle which causes the dispersed fluid to form droplets or

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bubbles. The fundamental conditions for this type of system to operate is that there is a sufficient density differential to support a counterflow and that the two fluids are immiscible and at different temperatures. Either fluid may be the heavier or lighter. Similarly, either fluid may be the hot or cold component. A robust model should be flexible enough to account for a variety of combinations, making appropriate selections of transfer expressions to accommodate any one of the four possible configurations.

Governing Equations

In modelling the one-dimensional response of the above described device, the axial dimension of the column is divided into control volumes. A set of governing ODEs for the control volumes is derived (Coban, 1986) from the Navier-Stokes equations by applying fundamental assumptions germane to one-dimensional steady state two phase flow. The result is a set of three - one momentum and two energy - equations describing the hydrodynamic and thermodynamic activity. The equation set is solved numerically for each control volume given a set of conditions existing at the boundaries. The governing set of ODEs are as follows:

$$\frac{dP}{dz} = -\frac{\dot{m}_d}{A}\frac{dU_d}{dz} - \frac{\dot{m}_c}{A}\frac{dU_c}{dz} - [\rho_c(1-\phi) + \rho_d\phi]g \qquad 1$$

$$\frac{di_d}{dz} = \frac{A}{\dot{m}_d}\frac{\dot{Q}_d}{V} \qquad 2$$

$$\frac{di_c}{dz} = -\frac{A}{\dot{m}_c}\frac{\eta\dot{Q}_d}{V} \qquad 3$$

with friction between the continuous fluid and device walls assumed negligible. This system can be solved numerically by the application of a Runge-Kutta scheme of an appropriate order. In this work a 4th order scheme is chosen.

Since the ODEs are comprised of a number of components which must be determined at each control volume location, it is necessary to have appropriate expressions for these components. A review of the literature - particularly of works by the individuals mentioned in Chapter 1 - provides candidate expressions for each of the various components. Generally, the expressions are empirically based. Where needed, theoretical derivations and modifications are developed. An underlying criterion for selecting expressions for use in the model is that they must be as universally applicable as possible. This presents some difficulty in that the set of expressions is large and some must be extended to cover ranges of conditions not specifically stated but not specifically excluded. Theoretical variations and modifications are discussed where appropriate in the following expressions.

Dispersed Fluid Velocity

Two separate expressions are used for determining dispersed droplet or bubble velocities. An expression from Raina et al. (1984) provides a correlation for rising ellipsoidal fluid particles.

Rising droplets

$$U_d = \frac{1.1547 \left[\{1 - \frac{\rho_d}{\rho_c} (\frac{R_o}{R})^3\}(\frac{2Rg}{C_D}) \right]^{1/2} D^{(\frac{5}{6} - \frac{D}{T_c})}}{\left[\frac{T_c^2 + T_d^2}{2 T_c T_d} \right]^{\rho} \left[\frac{C_{p_c} \mu_c}{k_c} \right]^{\frac{R_o}{1.6R}}}$$

4

Falling Droplets

A simpler expression cited by Raina which accounts for the effect of gravity on the density differential is used for falling droplets.

$$U_d = \left[\frac{4}{3} \left(\frac{\rho_d - \rho_c}{\rho_d} \right) \frac{2Rg}{C_D} \right]^{\frac{1}{2}} \qquad 5$$

Holdup

The holdup ratio is the ratio of dispersed fluid volume to total volume of a control volume segment. For any given location, the ratio is found by

$$\phi = \frac{\dot{m}_d}{\rho_d A U_d} \qquad 6$$

Continuous Fluid Velocity

The continuous fluid velocity is found from simple continuity.

$$U_c = \frac{\dot{m}_c}{A(1-\phi)\rho_c} \qquad 7$$

Drag Coefficient

Equations 4 and 5 require a droplet drag coefficient. A number of expressions are given in various references. A suitable expression is taken from White (1974, 1991):

$$C_D = \left[\frac{24}{Re} + \frac{6}{1+Re^{1/2}} + 0.4 \right] \cdot \left[\frac{1 + \frac{2\mu_c}{3\mu_d}}{1 + \frac{\mu_c}{\mu_d}} \right] \qquad 8$$

Equations 1-8 comprise the hydrodynamic modelling of a spray-column

DCHX and can be shown to simulate with reasonable accuracy, observed reactions

in a selection of applications. It must be noted that a single universally applicable

expression for every combination of fluids, flow rates, and DCHX geometries is

not found. The above set of expressions represent a generally good simulation

approximation of DCHX dynamics. Quantitative use of such a simulation for

micro analysis of DCHX operation must be kept in perspective.

Dispersed Droplet/Bubble Radius

The dispersed fluid droplet/bubble size is a key element of the velocity

expressions and Reynolds number calculations. Droplet/bubble radius is readily

determined if one notes that eliminating droplet/bubble breakup and/or

coalescence results in the conditions that droplet/bubble integrity is maintained.

Thus the droplet/bubble radius is determined by a simple conservation of mass.

$$R = R_0 \left(\frac{\rho_{d_0}}{\rho_d} \right)^{1/3} \qquad \qquad 9$$

Droplet/Bubble Population

Droplet/bubble population is a key element in the heat transfer calculation.

It is calculated from control volume size, droplet/bubble size and knowledge of the

holdup. In some works it has been assumed that control volume droplet/bubble

population per control volume remains constant along the length of a column. A

more detailed examination of continuity requirements suggests otherwise.

Asuming droplet/bubble integrity, if the control volume population were constant

then an increase in droplet/bubble size would affect the holdup. However, holdup is determined analytically from equation 6 and not linked to droplet/bubble size or population; therefore, a constant population is not possible. By noting that the mass flow rate and density in equation 6 reduces to a volumetric flow rate and that the time variable cancels with the time variable of the velocity term, the holdup ratio, ϕ (Equation 6), can be rewritten as

$$\phi = \frac{\frac{4}{3}\pi R^3 n_B}{Adz} \qquad 10$$

where n_B, the control volume droplet/bubble population, is introduced. This expresses the holdup more fundamentally to its definition and gives a means for determining the population for any given control volume.

$$n_B = \frac{\phi Adz}{\frac{4}{3}\pi R^3} \qquad 11$$

The total number of bubbles passing through a control volume *during a specified length of time* will be constant in keeping with continuity. However, the instantaneous population increases or decreases with a decrease or increase in droplet/bubble velocity, respectively.

Heat Transfer

The heat transfer mechanisms are of the most concern in modelling. It is described in the ODEs by the $\dot{Q}$ term in equations 2 and 3 and is the aggregate sum of the convective transfer to or from all droplets/bubble present in the control

volume. It is simply and classically expressed as

$$\dot{Q} = hA_B(T_c - T_d)\,n_B \qquad\qquad 12$$

The key element of equation 12 is the convection transfer coefficient, h. The coefficient must be determined for the two-phase (liquid or gas) or three-phase condition present at any given location in a DCHX. As pointed out in Chapter 1, the dispersed fluid can pass through a number of regimes (e.g. circulating, stable, phase change, etc.) as it passes through a device. This potentially requires a matrix of expressions for modelling since any or all regimes can be present in a given DCHX configuration.

Expressions for droplet/bubble convection heat transfer are available in the literature. Most are empirically based. Many are application specific. In selecting suitable candidates for use in modelling, like the hydrodynamics, only those that are most universally applicable are retained.

A difficulty exists in that not all regimes can be precisely modelled. Heat transfer at droplet injection is an example. This regime is characterized by high droplet circulation and can account for a substantial portion of the total heat transfer in two-phase liquid system (Culbreth, 1986). The findings upon which this statement is made are specific to a water/oil system where single oil droplets were injected into the continuous stream from a port consisting of a small tube. The tube allowed the continuous medium to flow nearly completely around the forming droplet and continue unimpeded. This injection process contrasts significantly with

what might actually be found in a commercial system where a spray nozzle large enough to provide numerous streams of droplets would be required and around which the continuous fluid would have to pass. The continuous flow would, at injection, be radically different from the interaction described by Culbreth. This suggests that the injection heat transfer may be attenuated, especially since the effect was found to occur in only approximately the first ten droplet diameters of rise.

In this modelling, the first two regimes are combined and not uniquely modelled. Rather, they are treated as a weighted influence. The influence is added to expressions used for describing the transfer coefficient for droplets in the next regime - stable rise. Reasonable modelling effort precludes any greater detail.

Stable Rise

Stable rise is characterized by a droplet rising with negligible internal circulation and stable geometric shape. Thus the transfer mechanism is that of exterior convection coupled with internal conduction, with the internal conduction resistance being the dominant factor. An expression for the external convection comes from Tochitani et al. (1977b), and is given as

$$h_T = \frac{k_c}{2R}\left(\frac{2|U_d|R}{\alpha_c}\right)^{1/3} \qquad 13$$

The internal resistance was studied by Sideman (1964), and is given by

$$h_s = .00375 \frac{2|U_d|R}{\alpha_c} \left[\frac{1}{1+\frac{\mu_c}{\mu_d}} \right] \frac{k_c}{2R} \qquad 14$$

The above two expressions are coupled in a series resistance combination which gives the convection transfer coefficient for the stable rise regime.

$$h_{sr} = \frac{h_s h_T}{h_s + h_T} \qquad 15$$

Injection/High Circulation Influence

A correlation for the internal transfer for rapidly circulating drops is cited by Jacobs (1988) as being recommended by Sideman (1966) for best determining the transfer for this type of droplet. The correlation is given as

$$h_{JS} = [2 + 1.13 (Pe\kappa)^{0.5}] \frac{k_c}{2R} \qquad 16$$

where

$$\kappa = 1 - 1.45 \frac{1+3 \frac{\mu_d}{\mu_c}}{1+\left(\frac{\rho_d \mu_d}{\rho_c \mu_c}\right)^{\frac{1}{2}}} Re_c^{-\frac{1}{2}} \qquad 17$$

Like the stable rise expression, the above expression is used in a series combination with the Tochitani expression for the exterior transfer. A decay function is used to facilitate the transition between this and the stable rise regime. The weighted decay is effective to approximately thirty droplet diameters. The final expression becomes

$$h_{inj/hc} = \frac{h_T h_{JS}}{h_T + h_{JS}} \left[1 - \left(\frac{z_{D_1}}{30} \right)^2 \right]$$ 18

Phase Change

The convection process for a droplet undergoing phase change was specifically studied with some limitations (Tochitani et al., 1977). One notes that a phase changing droplet adopts a liquid shell-like structure that cups around the vapor region. Tochitani studied the heat transfer process around a phase changing droplet to include a change of fluid quality up to approximately 0.5. This corresponds with a bubble that appears to be quite far along in the phase change since the quality is based on the ratio of mass changed. The physical size of the vapor portion would be considerable compared to the remaining liquid at a quality of 0.5. His observations led to the expression given below.

$$Nu = 0.463 Pe_c^{1/3} (\pi - \beta + 0.5 \sin 2\beta)^{2/3}$$ 19

wherein a transfer coefficient is obtained

$$h_T = .463 Pe_c^{1/3} (\pi - \beta + 0.5 \sin 2\beta)^{2/3} \frac{k_c}{2R}$$ 20

β, the droplet half opening angle used in the above two expressions, is described as shown in Figure 6 and defined analytically as

$$3\cos\beta - \cos^3\beta + 2 = \frac{4(1 - X_d)}{1 + X_d(M - 1)}$$ 21

where X_d is the droplet's quality and M is the ratio of liquid density to vapor density.
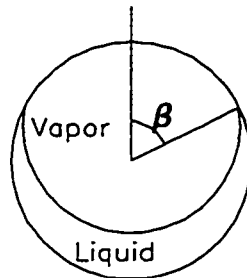
Figure 6 Geometry of Droplet Undergoing Phase Change with Droplet Half Opening Angle, β, Defined.

At a point at which the quality reaches approximately 0.5, an expression is required for the predominantly vapor bubble structure. This structure exhibits some circulation and rises at a higher velocity than while the fluid was liquid. Some works, including Coban's, viewed the vapor portion as non circulating and thus attributed a high resistance to this region, resulting in little or no heat transfer. It can be argued that low internal bubble viscosity allows for circulation. Of the several heat transfer expressions explored, the most reasonable is one for a spherical cap bubble derived from a mass transfer analogy of the heat transfer taken from Fan and Tsuchiya (1990), given by

$$Sh = 1.79 \frac{(3E^2+4)^{2/3}}{E^2+4} Pe^{1/2} \qquad\qquad 22$$

Noting that heat and mass transfer are approximately related by

$$\frac{Sh}{Nu} = \left(\frac{Sc}{Pr}\right)^{1/3} \qquad\qquad 23$$

then

$$h_{FT} = \left[1.79\frac{(3E^2+4)^{2/3}}{E^2+4}Pe^{1/2}\right]\left(\frac{Pr}{Sc}\right)^{\frac{1}{3}}\frac{k_c}{2R} \qquad 24$$

As was the case in the earlier regimes, a weighted combination of this and the Tochitani correlation is constructed. The weighting gradually filters in the spherical cap correlation. The Tochitani correlation is primary for droplet/bubble qualities less than 0.5, whereas the Fan and Tsuchiya expression is primary for qualities greater than 0.5. The weighted expression is

$$h_{ph} = (1-X_d^2)h_T + X_d^2 h_{FT} \qquad 25$$

Vapor Bubble Rise

Coban and Boehm (1986), developed a method for determining the heat transfer to or from a vaporized bubble based on the assumption that the bubble's vapor interior is stable (noncirculating). They noted that for the experimental cases they studied, the vapor bubble traveled through a portion of the continuous medium in which the temperature profile was more or less linear. As a result, they used an expression from Carslaw and Jaeger (1959) for the temperature distribution inside a sphere subject to a linearly increasing surface temperature. Neglecting the oscillatory terms, they used the expression to find the difference between the average temperature inside the sphere and its surface, which then would allow them to set up a conduction expression for the sphere at the surface. As mentioned, an assumption was made that the temperature of the surface would

be that of the continuous fluid, and for most cases this would be approximately so, with only small error.

Following a similar analysis but beginning with an alternative expression from Carslaw and Jaeger that gives the interior temperature profile of a sphere due to the heat transfer from a continuous medium with a linearly varying bulk temperature, an expression is derived for the vapor bubble rise. This expression differs from the one used by Coban in that it does not presume the bubble surface equals the continuous medium temperature but rather relies on an exterior convective transfer coefficient. Like the Coban and Boehm analysis, only the steady state portion of this expression is used. The average interior and surface temperatures are found, and a conduction relation is set up. The starting expression is given by

$$T(r, t) = \gamma \left[t + \frac{r^2 RH - R^2 (2 + RH)}{6 \alpha RH} \right]$$ 26

Appendix I contains a full derivation of the expression, describing the step by step reduction and use in a heat transfer expression given by

$$\dot{Q} = k_v A_B \frac{\gamma R}{3\alpha} = h_B A_B \gamma \left[\frac{R}{3\alpha \frac{h_o}{k_v}} + \frac{R^2}{15\alpha} \right]$$ 27

An expression for the overall transfer coefficient which accounts for the outside convection and interior conduction into a vapor bubble in the vapor bubble rise regime, h_{vbr} (h_B in above), can be defined as

$$h_{vbr} = \frac{5h_o k_v}{5k_v + Rh_o} \qquad 28$$

This expression is similar to the expression used by Coban and Boehm in that it represents the series combination of the exterior convection resistance and the internal conduction resistance (See Appendix I). By noting that a separation of terms yields

$$h_{vbr} = \left[\frac{1}{h_o} + \frac{R}{5k_v}\right]^{-1} \qquad 29$$

the individual resistances are revealed. The last term is the same "*internal convection*" term derived by Coban and Boehm.

The h_o term is the convection coefficient acting between the continuous medium and the exterior surface of the bubble. A suitable expression for this term comes from work by Steinberger and Treybal (1963), cited by Sideman (1966) and is given as

$$h_o = h_{STr} = [2 + .569(GrPr)^{.25} + .347Re_c^{.62}Pr^{.31}]\left(\frac{k_c}{2R}\right) \qquad 30$$

It is of note to observe that if $5k_v/R << h_o$, then the heat transfer will be dominated by the $5k_v/R$ term

$$h_{vbr} = \frac{5k_v}{R} \; ; \; \left(\frac{5k_v}{R} << h_o\right) \qquad 31$$

which is the Coban and Boehm result. In selecting the alternative starting

expression, the same conclusion is essentially reached. The improvement in this version is that the external convection resistance around a vapor bubble is retained vis a vis assuming it to be negligible. Though a low exterior resistance (compared to higher internal resistance) is usually the case, an exception might occur in cases where bubbles of a gas with highly conductive properties rise through a liquid of poorly conductive properties. For modeling accuracy and versatility in simulating a wide range of candidate fluids, the new expression is incorporated.

The difference between the development of equation 28 and the development for the phase change regime is the assumption of a stable vapor bubble compared to a circulating vapor cap on the two-phase bubble. To facilitate a smooth transition between the regions, a weighting function is once again used to gradually eliminate the influence of the previous regime during the first ten bubble diameters of the stable vapor rise. The expression becomes

$$h_{vbr_{transition}} = .5h_{vbr} + .5h_{PT}\left[1-\left(\frac{z_{D_b}}{10}\right)^2\right] \qquad 32$$

Equations 13-32 comprise the matrix of expressions required for determining the heat transfer to/from droplets/bubbles.

Mass Transfer

Mass transfer effects are not modelled, though with some modification to the governing equations and the addition of several more supporting expressions,

they could be. An alternative form of equation 3 would appear as

$$\frac{di_c}{dz} = -\frac{A}{\dot{m}_c}\frac{(\eta\dot{Q}_d + \dot{m}_{cd}i_{fg_c})}{V}$$

33

Note the inclusion of the term which accounts for the small amount of mass transfer occurring between the continuous fluid and a dispersed bubble. It is mentioned here for completeness though its significance is minor since mass transfer effects only apply to vapor-liquid interface conditions. If one eliminates the two-phase liquid-liquid and the three-phase preheating and phase change cases, and considering that the small amount of heat transferred due to vaporizing mass is negligible compared to the normal convective transfer in large systems, the total influence of mass transfer in modelling is small.

Thermodynamic, Thermophysical, and Diffusion Variables

Key variables, such as pressure, temperature, quality, density (or specific volume), and enthalpy, as well as additional supporting properties such as viscosity and conduction coefficients are determined from a specialized ensemble of subroutines. In the case of the thermodynamic (state) variables, a set of subroutines developed by Reimer et al. (1976a, 1976b, 1976c) is used. These routines take the input of any two of the five state variables and return the remaining three. Separate ensembles for water, hydrocarbons, and freons are included in the simulation and are integral to the modelling architecture. For those fluids not included in the Reimer routines, a special subroutine was

constructed to provide thermodynamic values based on a curve fit of published tabulated data. Appendix IV lists the curve fit expressions used.

Thermophysical properties are determined from a subroutine written specifically for this work. Values are determined from a curve fit of tabulated data spanning reasonably wide ranges of temperatures. Data is derived from numerous sources such as Vargaftik (1975) and handbooks, (ASHRAE, 1989).

Diffusion

As noted above, a portion of the heat transfer analysis is based on the mass transfer analogy. Cussler (1984) details a method for determining the diffusion coefficient from the Chapman-Enskog theory. The calculations are easily coded into a subroutine and require only a few key characteristics of the gasses involved. The coefficient is found by

$$D = \frac{1.86 \cdot 10^{-3} T^{3/2} \left(1/\tilde{M}_1 + 1/\tilde{M}_2\right)^{1/2}}{P\sigma_{12}^2 \Omega} \qquad 34$$

where $\tilde{M}_1$ and $\tilde{M}_1$ are the molecular weights of the fluids/gasses and σ_{12} and Ω are molecular property characteristics detailed in the theory presented by Cussler. Expressions for these quantities, while not extensive, require some study of the theory. The quantity Ω, for example, is determined from tabulated data. As a result, the expressions are not repeated here.

ODE Solution Scheme

A solution to the governing equations (Eqs 1-3) is accomplished with a

fourth order Runge-Kutta numerical scheme which is discussed in any of a number of texts on numerical analysis. Simply expressed, the scheme takes the following form for a function $y(x)$ utilizing a step size, h.

$$y_{i+1} = y_i + \frac{1}{6}(K_1 + 2K_2 + 2K_3 + K_4) \qquad 35$$

where

$$K_1 = hF(x_i, y_i) \qquad 36$$

$$K_2 = hF(x_i + \frac{h}{2}, y_i + \frac{1}{2}K_1) \qquad 37$$

$$K_3 = hF(x_i + \frac{h}{2}, y_i + \frac{1}{2}K_2) \qquad 38$$

$$K_4 = hF(x_i + h, y_i + K_3) \qquad 39$$

and noting that the function, F, is the first derivative - defined by one of the ODEs - of the variable of interest.

The solution requires boundary conditions for the variables in the ODEs. Pressure, mass flow rates and both fluid velocities, as well as densities can be determined at the starting boundary (bottom of the column). However, only one temperature is known at this location. The other is known at the opposing end of the counterflow system. A solution, then, requires a guess of the temperature at the unknown location to fill out the compliment of boundary conditions. The Runge-Kutta is then allowed to *march* along the solution until the top of the column is reached, where a check is made of the temperature which was guessed at with the known specification. If the check reveals a temperature that is too

high (or too low) , a downward (or upward) revision of the guess is made by bisecting the interval between the previous guess and upper or lower inlet temperature limit upon which the Runge-Kutta scheme is run again. This process - well known as a *shooting method* - is repeated until the solution marches to a correct ending temperature for the guessed variable.

Variable Mapping

The solution of the differential equations is accomplished by first calculating all the necessary supporting variables from known conditions from boundary conditions or previous control volumes and then using these variables in the differential equation set, always using updated values as they become available in the calculation order. An algorithm sets the order of calculation for the variables. It is desirable, for obvious reasons, that dependent variables are calculated with updated values of the variables upon which they depend as the solution *marches* along the length of the DCHX. Values of the fluids' densities, enthalpies, pressure, and temperature are readily available and independent of many of the physical quantities such as velocity and droplet size. The physical quantities are often dependent on other physical quantities and therefore occasionally mutually dependent. For these cases, values of certain variables from previous step in the solution scheme are used. Fortunately, the necessity for these approximations are quite few if the following mapping order is followed.

First, known values of the system pressure, P, and the fluids' temperatures are assigned and tracked. From this information, enthalpy, density, and quality are

found from subroutines. The temperature is then used to ascertain the

thermophysical properties - also from subroutines. Velocities are determined

from input mass flow rates and entry conditions which then yield beginning holdup

ratios. Velocity gradients are assumed to be zero at z=0 and then calculated by

$$\left(\frac{dU}{dz}\right)_i = \frac{U_i - U_{i-1}}{dz} \qquad 40$$

The simplest of the remaining dependent variables to calculate is the

droplet radius, which depends only on the changing density, one of the first items

known in the variable calculation algorithm. The complete order of variable

determination is then

$\dot{m}_d \ \dot{m}_c \ R_0 \ A \ L \ dz \ x_c$ - input values

$P \ i_c \ i_d$ - from boundary conditions or previous step

$T_c \ T_d \ \rho_c \ \rho_d \ x_d$ - from fluid state subroutines

$\mu_c \ \mu_d \ k_c \ k_d \ c_p \ Pr$ - from thermophysical property routines - function of

(T,P)

For the i_{th} calculation

$R \quad (\rho_d)$

$\beta \quad (\rho_d \ x_d)$

$Re \quad (\rho \ U_{i-1} \ R \ \mu)$

$C_D \quad (Re \ \mu)$

$U_d \quad (\rho \ R \ g \ C_D \ T \ c_p \ k)$

$$\phi \quad (\dot{m}_d \quad A \quad U_d \quad \rho)$$

$$U_c \quad (\phi \quad \dot{m}_c \quad A \quad \rho_c)$$

$$U_d' \quad (U_d \quad dz)$$

$$U_c' \quad (U_c \quad dz)$$

$$n_B \quad (A \quad dz \quad R \quad \phi)$$

$$h \quad (Re \quad Pr \quad Gr \quad R \quad \beta \dots \text{ and properties dependent on above})$$

$$\dot{Q}_d \quad (h \quad R \quad n_B \quad T_c \quad T_d \quad k_c \quad k_d)$$

For the (i_{th}+1) calculation (a result of a step in the Runge-Kutta solution of the ODEs)

$$P \quad (\dot{m}_d \quad \dot{m}_c \quad U_d' \quad U_c' \quad \rho_d \quad \rho_c \quad g \quad \phi \quad A)$$

$$i_d \quad (A \quad \dot{m}_d \quad Q_d \quad R)$$

$$i_c \quad (A \quad \dot{m}_c \quad Q_d \quad R)$$

The significance of this mapping is that only the Reynolds number requires using the dispersed velocity from the previous control volume so that it can be used in the drag coefficient and subsequently to find the new dispersed velocity value. With the variables calculated, the fourth order Runge-Kutta scheme can be implemented to find the pressure and enthalpy for the next (i_{th}+1) location from which the temperatures, densities, and quality are found and carried forward for the next calculations.

Optimizing a Configuration for Dual Fluid Utility

As discussed in Chapter 1, optimization of a given DCHX depends on a number of parameters, not the least of which is the type of optimization - maximum extraction, target temperature, dual fluid utility, etc. - desired. The conditions of dual utilization are that both fluids undergo the same temperature excursion and that the differential at any given location, particularly at the ends, be a minimum. An indicator that accurately portrays whether or not this condition is met must account for both the parallelism in the profiles and the closeness of approach. Such an indicator is developed for evaluating the case of dual utility optimization. With this indicator, the ideal case - coincidental curves are achieved - is reflected by a value of 1.0. Any condition away from the ideal shows up as a degraded value (less than 1.0) with less and less desirable cases tending asymptotically to 0.

Heretofore, system evaluation has relied on traditional log mean temperature difference and various effectiveness measures to assess system performance. As stated, for the dual utility criterion, these measures fail, requiring an alternative means of measure. Appendix II outlines the development of a new indicator - hereafter referred to as the Dual Utilization Optimization (DUO) indicator - that identifies when dual utility is achieved. The indicator is defined by the following expression

$$DUO = \left(1 - \frac{LMTD}{\Delta T_{max}}\right)\left(1 - \left|\frac{\Delta T_{inlet} - \Delta T_{outlet}}{\Delta T_{max}}\right|\right) \qquad 41$$

The utility of this indicator is that it yields a value ranging between 0 and 1 with 1 being, theoretically, the ideal case. (It is noted that one cannot achieve the so called *ideal* case - coincidental profiles - since temperature profiles falling on top of each other would mean zero differential, resulting in no heat exchange.) The indicator is calculated and recorded as one or more parameters are varied over a target range. The optimum value of the parameter is found when a peak occurs in the indicator value, signifying that optimum dual utility has been reached. The peak will be some value less than 1 but generally will range above .75 in systems achieving dual utility. The indicator is of most use in two-phase systems due to more well behaved nature of the temperature profiles. The advantages of using this indicator are shown in the results presented in Chapter 3.

Two-Dimensional Modelling for Sieve Tray Analysis

It is desirable to expand one-dimensional modelling to two-dimensions for analyzing certain effects of DCHX enhancements such as the introduction of sieve-trays into the axial flow. To accomplish this, it is desirable to limit the analysis to examining a single module (two consecutive trays) of a sieve-tray stack and generating a schematically correct two-dimensional representation. Modelling of the continuous fluid flow is accomplished using commonly used computational fluid dynamics (CFD) methods. With the continuous fluid flow field known, the path of a rising droplet can be determined and plotted. Droplet path traces allow

for calculating the heat transfer increase due to the apparent increase in relative

velocity seen by a droplet. A comparison is made to a spray-column case. The

first step of this process is the modelling of the two-dimensional flow of a sieve-

tray module.
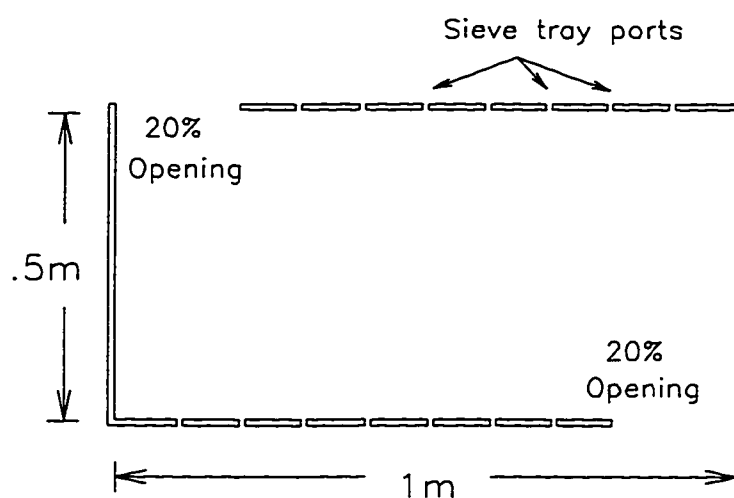
Figure 7 Schematic of Sieve-Tray Module (Two-Dimensional Model).

Flow Field Modelling

The velocity field of the sieve-tray module depicted in Figure 7 can be found by solving the two-dimensional vorticity transport equation given as

$$\frac{\partial \omega}{\partial t} + u\frac{\partial \omega}{\partial x} + v\frac{\partial \omega}{\partial y} = \nu\left(\frac{\partial^2 \omega}{\partial x^2} + \frac{\partial^2 \omega}{\partial y^2}\right) \qquad 42$$

The solution of the transport equation is then used in the stream function relationship

$$\nabla^2 \psi = -\omega \qquad 43$$

In turn, the solution of the stream function equation yields the velocities from the commonly known relationships

$$u = \frac{\partial \psi}{\partial y} \qquad 44$$

and

$$v = -\frac{\partial \psi}{\partial x} \qquad 45$$

The above equations can be solved numerically through a variety of methods found in references such as Roache (1972). A method well suited for solving vorticity transport is the Alternating Direction Implicit (ADI) method, specifically, the Peaceman-Rachford ADI method. Formally, the two steps are denoted (using Roache's notation) by

$$\frac{\omega^{n+1/2}-\omega^n}{\Delta t/2} = -u\frac{\partial \omega^{n+1/2}}{\partial x} - v\frac{\partial \omega^n}{\partial y} + \nu\frac{\partial^2 \omega^{n+1/2}}{\partial x^2} + \nu\frac{\partial^2 \omega^n}{\partial y^2} \qquad 46$$

$$\frac{\omega^{n+1}-\omega^{n+1/2}}{\Delta t/2} = -u\frac{\delta \omega^{n+1/2}}{\delta x} - v\frac{\delta \omega^{n+1}}{\delta y} + \nu\frac{\delta^2 \omega^{n+1/2}}{\delta x^2} + \nu\frac{\delta^2 \omega^{n+1}}{\delta y^2} \qquad 47$$

The discretized forms of these equations are

$$\frac{\omega_{i,j}^{n+1/2}-\omega_{i,j}^n}{\Delta t/2} + u_{i,j}\left(\frac{\omega_{i+1,j}^{n+1/2}-\omega_{i-1,j}^{n+1/2}}{2\Delta x}\right) + v_{i,j}\left(\frac{\omega_{i,j+1}^n-\omega_{i,j-1}^n}{2\Delta y}\right)$$

$$= \nu\left(\frac{\omega_{i+1,j}^{n+1/2}-2\omega_{i,j}^{n+1/2}+\omega_{i-1,j}^{n+1/2}}{\Delta x^2}\right) + \nu\left(\frac{\omega_{i,j+1}^n-2\omega_{i,j}^n+\omega_{i,j-1}^n}{\Delta y^2}\right) \qquad 48$$

$$\frac{\omega_{i,j}^{n+1}-\omega_{i,j}^{n+1/2}}{\Delta t/2} + u_{i,j}\left(\frac{\omega_{i+1,j}^{n+1/2}-\omega_{i-1,j}^{n+1/2}}{2\Delta x}\right) + v_{i,j}\left(\frac{\omega_{i,j+1}^{n+1}-\omega_{i,j-1}^{n+1}}{2\Delta y}\right)$$

$$= \nu\left(\frac{\omega_{i+1,j}^{n+1/2}-2\omega_{i,j}^{n+1/2}+\omega_{i-1,j}^{n+1/2}}{\Delta x^2}\right) + \nu\left(\frac{\omega_{i,j+1}^{n+1}-2\omega_{i,j}^{n+1}+\omega_{i,j-1}^{n+1}}{\Delta y^2}\right) \qquad 49$$

In breaking up the process into two steps, the method creates two tri-diagonal matrices which are solved using commonly found subroutines.

Boundary conditions for set up described by Figure 7 are as follows. 1) Velocity (u,v) is zero along all walls. 2) Constant and equal vertical inlet/outlet velocity is imposed at the upper and lower 20% openings. 3) Vorticity is assumed zero along all boundaries; however, with each iteration on the solution, values at physical boundaries are updated using a forward or backward projection from locally adjacent nodes in the field. 4) The stream function is assumed zero along

on continuous section of wall (i.e. left and lower segments). Incremental stream

function changes across the field are summed until they reach the other

continuous wall (upper and right). A check is made that to insure stream function

is constant along the second surface.

A solution to Poisson's equation (Eqn 43) is found through the use of a

Successive Over-Relaxation (SOR) method. Roache presents the following

expression for implementing the SOR to the Poisson equation.

$$\psi_{i,j}^{k+1} = \psi_{i,j}^{k} + \frac{w_o}{2(1+\beta^2)} [\psi_{i+1,j}^{k} + \psi_{i-1,j}^{k+1} + \beta^2 \psi_{i,j+1}^{k} + \beta^2 \psi_{i,j-1}^{k+1}$$

$$-\Delta x^2 \omega_{i,j} - 2(1+\beta^2) \psi_{i,j}^{k}]$$

50

where

$$\beta = \frac{\Delta x}{\Delta y}$$

51

$$w_o = 2\left(\frac{1-\sqrt{1-\xi}}{\xi}\right)$$

52

$$\xi = \left[\frac{\cos\left(\frac{\pi}{I-1}\right) + \beta^2 \cos\left(\frac{\pi}{J-1}\right)}{1+\beta^2}\right]^2$$

53

ADI and SOR methods are discussed in detail in the cited reference. It is noted

here that w_o is an optimized weighting factor based on the grid's aspect ratio.

Grid spacing is based on two factors - field location that is of most interest

and computational requirements limitation. The aspect of most interest in this

study is the path of droplets rising between the trays and their interaction with the continuous fluid in the central region of the module. Motion near the walls (in the boundary layer) is generally not important for this analysis. As a result, a relatively coarse grid suffices. The 1.0m x 0.5m module of Figure 7 is sectioned into a 22 x 22 grid. This sizing is selected so that when the boundary nodes are eliminated, a 20 x 20 grid of unknowns remains - a computationally economical size. A solution for the vorticity, stream function and velocities converges quickly, yielding a field that retains the characteristics of simple potential flow. A check of boundary layer buildup reveals that for the flows that are run, the buildup is less that the spacing of one grid. A coarse grid is satisfactory since a boundary layer study is not relevant to the overall scope of interest. Applying the above methods yields a mapping of the flow field velocity.

The paths of individual bubbles can be determined by numerically placing droplets at varying locations along the bottom tray and tracking them as they rise - two-dimensionally - through the flow field. Vertical velocity is determined using the expression stated for the one-dimensional simulation. Horizontal velocity is found through the simple application of physics. The horizontal component of flow will produce a horizontal drag force on an individual bubble that can be used in a simple mass-acceleration relationship.

$$F_{b_x} = m_b a_{b_x} = \frac{1}{2} C_{d_x} \rho \, (U_{c_x} - U_{b_x})^2 S_b \qquad 54$$

wherein the horizontal acceleration is found by

$$a_{b_x} = \frac{\frac{1}{2}C_{d_x}\rho\,(U_{c_x}-U_{b_x})^2 S_b}{m_b} \qquad 55$$

With the acceleration known, both the droplet's location and total relative and absolute velocity can be determine from the classical physical relations

$$U_{b_x} = U_{b_{x_0}} + a_{b_x}\Delta t \qquad 56$$

$$x_b = x_0 + U_{b_x}\Delta t \qquad 57$$

$$y_b = y_0 + U_{b_y}\Delta t \qquad 58$$

$$|\vec{U}_b| = \sqrt{(U_{c_x}-U_{b_x})^2 + U_{b_y}^2} \qquad 59$$

noting that the droplet's relative vertical velocity is determined from the dispersed fluid velocity equation cited earlier in this chapter.

The heat transfer is determined from the appropriate transfer coefficient correlation - in this case, liquid drops rising through a liquid continuous fluid flow. It will be shown that the effect of the two-dimensional flow results in droplets that experience higher heat transfer due to the added horizontal component to the relative velocity.

Relatively few simplifying assumptions are made for this additional analysis over the one-dimensional case, the only significant one being that the continuous fluid remains at a constant temperature while within the confines of the sieve-tray

module. This is reasonable since for cases such as water/n-pentane, the total temperature excursion of the continuous fluid (water) is only approximately 10° - $12^\circ C$ over a column length of three meters, a bulk of which occurs during phase change. A one-meter module located in the preheating liquid-liquid portion experiences only a small temperature move. Another reason for this is that only single droplets are tracked, and thus any artificial temperature change would itself have to be an approximation.

Coding, Compiling, and Computing Requirements

Encoding of the algorithms and expressions described in this chapter is done in FORTRAN 77. The model was loaded and run on the Cray YMP2/216 supercomputer operated at the National Supercomputing Center for Energy and the Environment (NSCEE) located at the University of Nevada, Las Vegas. All modelling is written to be stand-alone, requiring no external library routines. A FORTRAN compiler resident on the NSCEE supercomputer optimally compiled the code (no special features invoked) for execution on the Cray YMP2/216.

Generally, runs made with the one-dimensional model required 30 to 50 seconds of CPU time on the Cray YMP2/216. Typically 20 to 35 iterations were required for a shooting method to find a solution. Solutions of the two-dimensional flow field converged quickly due to the relatively coarse (20x20) grid. Typically, solutions were reached in less than 6 iterations.

CHAPTER 3

RESULTS AND ANALYSES

One-Dimensional Simulation

A comparison is made of the results predicted by the one-dimensional

simulation model to experimental results. The comparison is made to validate the

selection of expressions and algorithms. Generally, the model predicts reasonably

well.

Experimental data comes from work by Coban, performed at the University

of Utah, where a 3-meter spray-column of .61 meter diameter was constructed for

operating a three-phase spray-column DCHX. The system dispersed n-pentane

through a flow of hot water at pressures ranging to approximately three

atmospheres. Flow rates and initial temperatures were controlled to provide a

range of combinations. Results and discussions of this experimental work was

published (Coban, 1986). The principle observations made in the experiments

were that of the entry and exit temperatures of the two working fluids. It is

against selected cases from this work that the output of this modelling is

compared.

Figures 9 through 11 show comparisons to three experimental cases studied

by Coban conducted on a 3.0 m (column length) by .305 m (column radius)

51

DCHX which dispersed n-Pentane into water with initial droplet radii of 2.0 mm. The comparisons cover a variety of flow rates, pressures, and starting temperatures. The results of the simulations are depicted by the solid line profiles. The inlet and outlet temperatures are known from the experiments and are shown as symbols.

Figure 9 shows a close correlation with experimental data is achieved. The known conditions of the water are the inlet and outlet temperatures of 85°C and 71°C and for the n-pentane, 41°C and 71°C, respectively. The simulation of a system operating under the same conditions results in entry and exit temperatures identical to the experimentally observed results.

Figure 10 shows a comparison to observed results to the spray-column operating at a narrower inlet temperature differential. It is seen here that the simulation diverges somewhat at the exit temperatures. The n-pentane did not rise to the same observed value. The simulation prediction was that there was incomplete vaporization while experimental observations show completion of vaporization. Though the divergence appears significant, it is noted that vaporization in the simulation was nearing completion, at which time the temperature would rise as rapidly as it did in Figure 9. The comparison in Figure 10 suggests some refinement could be made to the transfer coefficient expressions.

Figure 11 shows a comparison where the inlet temperature differential increases to a spread of 85°C to 31°C. The results of this simulation show a reasonable correlation to the known data, indicating that the heat transfer algorithm is fairly well constructed.

52
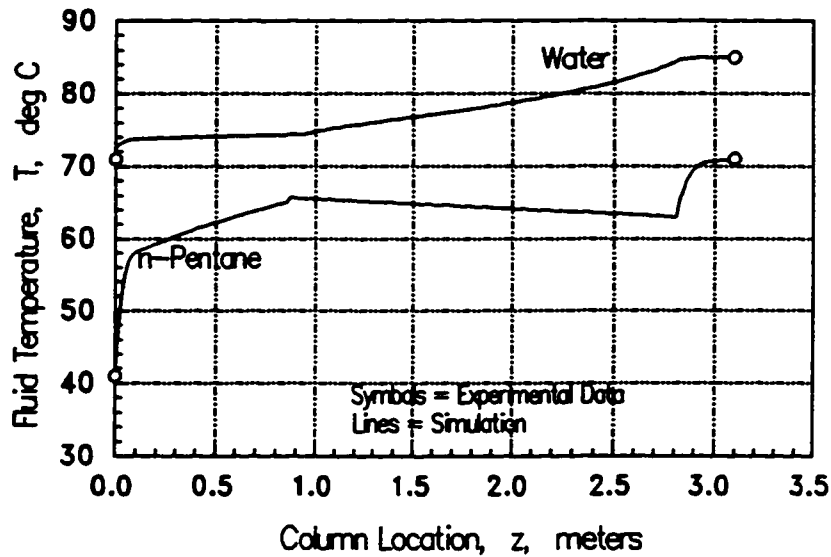
Figure 9 Comparison of Simulation Results to Experimental Data. (Pressure = 260 kPa, Water Rate = 1.94 kg/s, n-Pent Rate = .21 kg/s.) (Data from Coban, 1986).
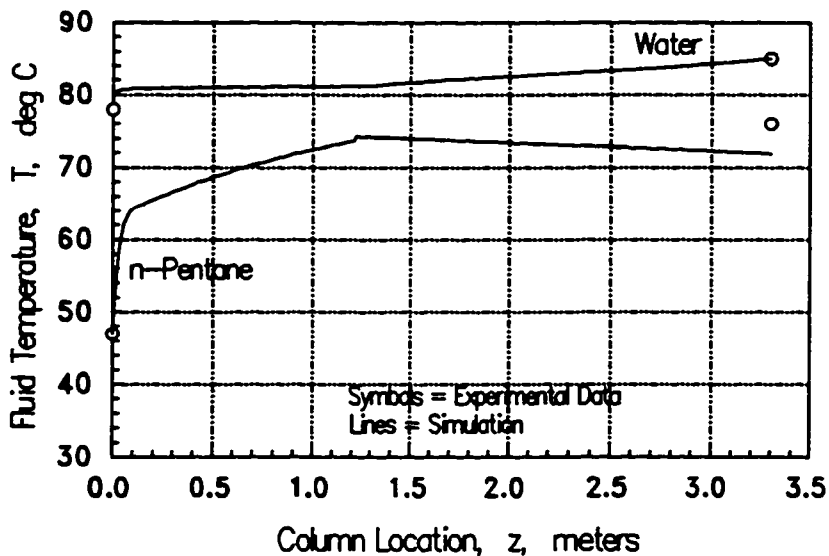
Figure 10 Comparison of Simulation Results to Experimental Data. (Press = 329 kPa, Water Rate = 2.11 kg/s, n-Pent Rate = .12 kg/s.) (Data from Coban, 1986).
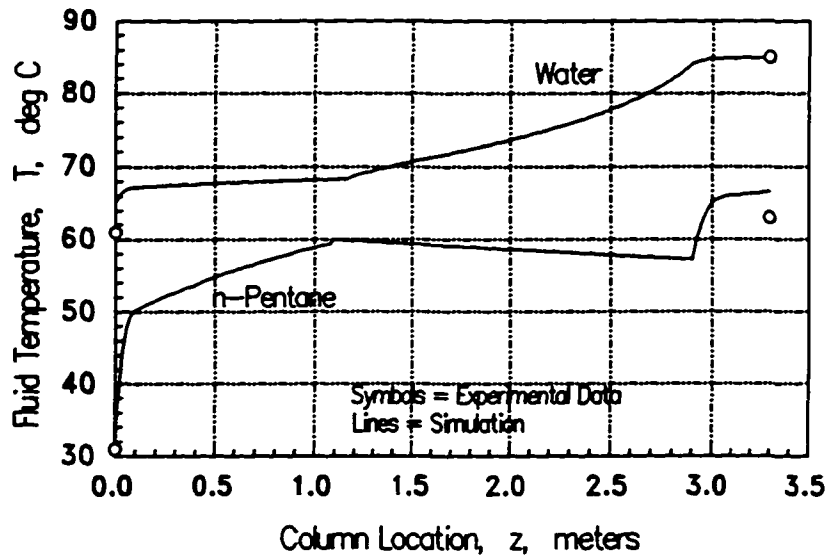
Figure 11 Comparison of Simulation Results to Experimental Data. (Press = 225 kPa, Water Rate = 1.52 kg/s, n-Pent Rate = .25 kg/s.) (Data from Coban, 1986.)

Individual droplet/bubble rise regimes are discernable in the profiles. The expected rapid temperature rise occurring in the first few centimeters of column corresponds to the high circulation condition present at droplet injection and initial rise. Following that, the attenuated rise occurring in the first meter corresponds to the stable liquid rise regime. This continues until the dispersed fluid reaches its saturation temperature, at which time phase change occurs. It is seen that during phase change, there is a decrease in dispersed fluid temperature. This is the result of the reduction in hydrostatic pressure seen by the droplet/bubbles as they rise through the column. The reduction in pressure lowers the saturation temperature. The vaporization process hastens as the process nears completion of the phase change. This is attributed to increased size and

circulation effects of the vapor cap on the bubble. Upon completion of

vaporization, the bubble rises rapidly and circulation once again decays.

In each of the three figures, the continuous fluid temperature is more or

less unremarkable since water has a higher specific heat and remains at a constant

state. Generally, it is of less interest, though no less important, than the working

dispersed fluid.

Details of the dispersed droplet/bubble characteristics such as droplet

radius, quality and holdup can be of interest but are generally difficult to obtain in

experimental work. Simulation offers some predictability. Figures 11 to 17 depict

a variety of key parameters for the three-phase baseline situation of Figure 9.

Figure 12 depicts the values of the heat transfer coefficient for the

droplet/bubble rising through the column. The transfer coefficient profile confirms

the temperature profile. The circulation influence which decays rapidly shows up

at the outset, following droplet injection. This is followed by a lower stabilized

value for the stable rise regime until the onset of vaporization. The weighting of

the Tochitani expression and the Fan and Tsuchiya expression during phase

change is seen in the saddle-shaped portion of the profile. The Tochitani

expression is quite high at the onset of phase change and decreases. The Fan and

Tsuchiya prediction begins to pick up when droplet/bubble quality reaches

approximately 0.5 and then increases as the vapor cap grows until vaporization is

complete. This elevated value then undergoes a final decay as the bubble rises to

its exit.
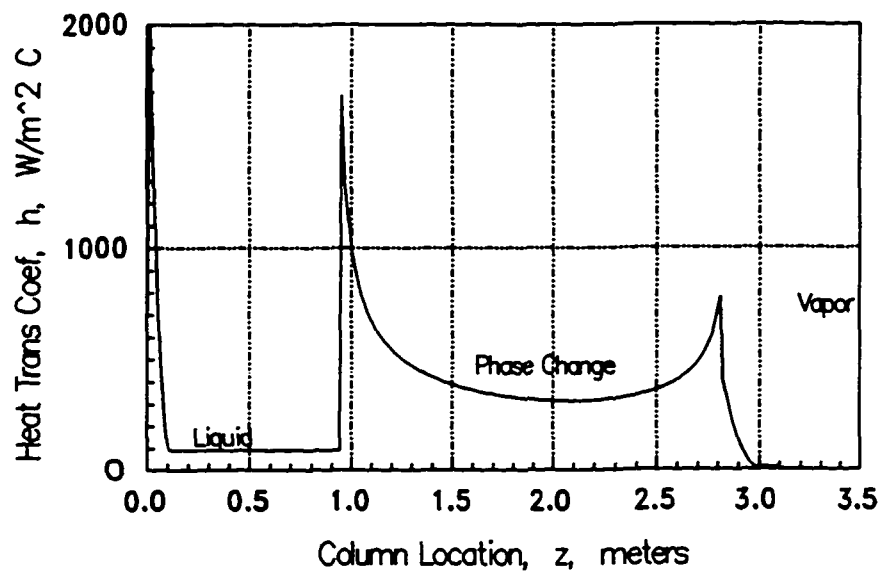
Figure 12 Droplet/Bubble Heat Transfer Coefficient Profile for Simulation Shown in Figure 8.
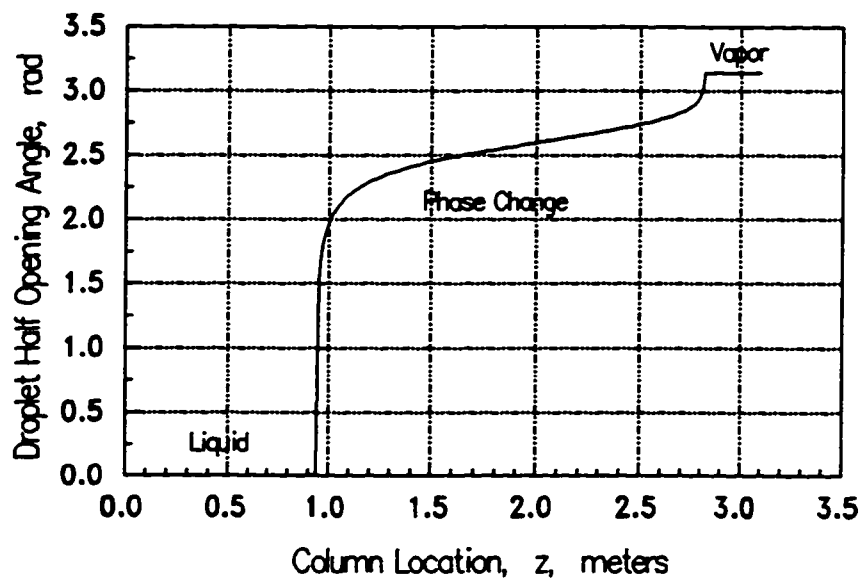
Figure 13 Droplet/Bubble Half Opening Angle Profile for Simulation Shown in Figure 8.
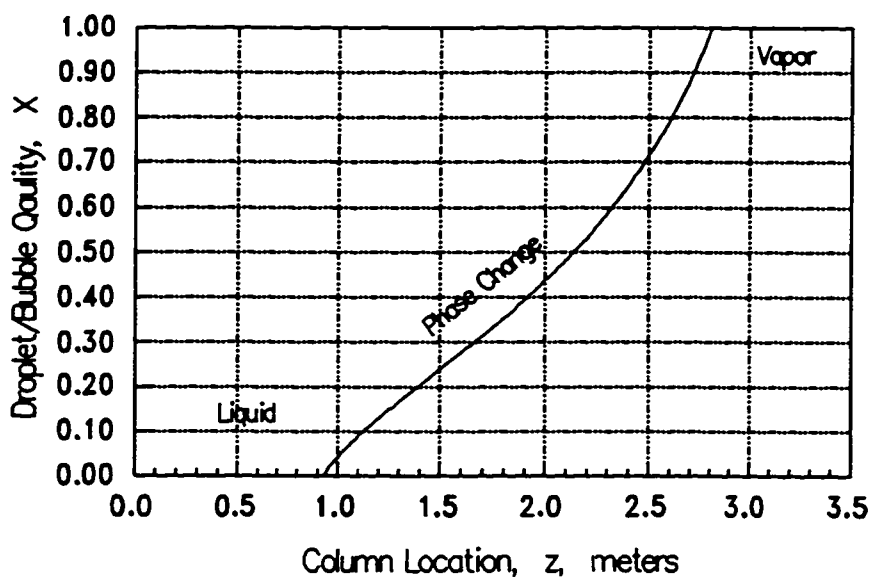
Figure 14 Droplet/Bubble Quality Profile for Simulation Shown in Figure 8.
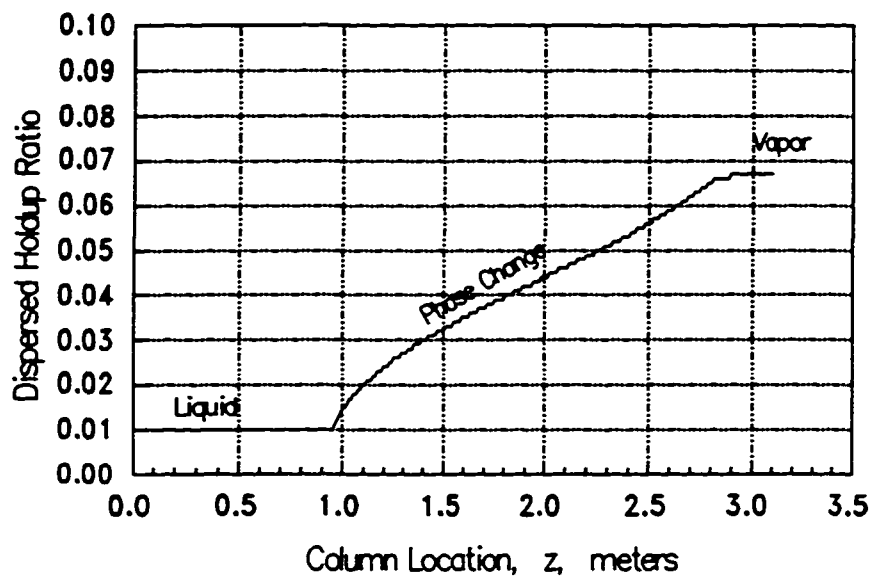
Figure 15 Dispersed Fluid Holdup Profile for Simulation Shown in Figure 8.
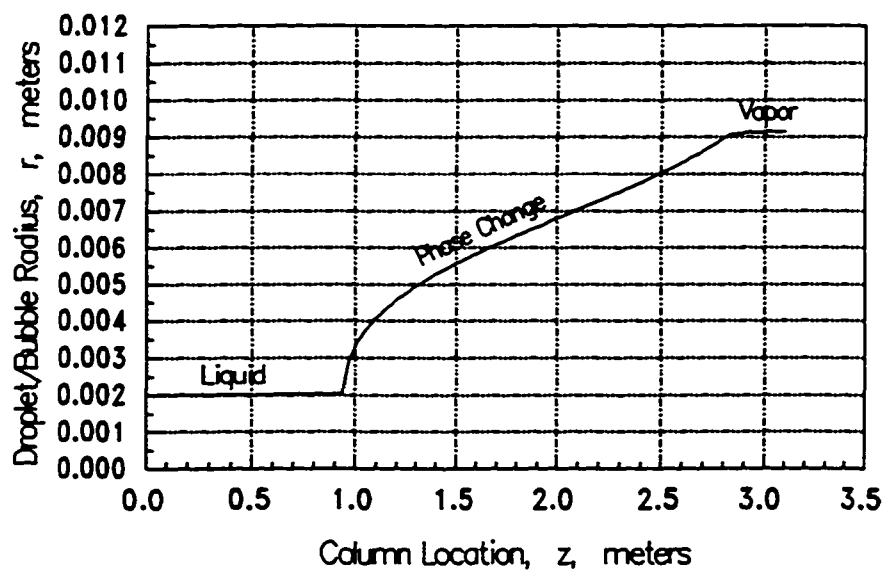
Figure 16 Droplet/Bubble Radius Profile for Simulation Shown in Figure 8.
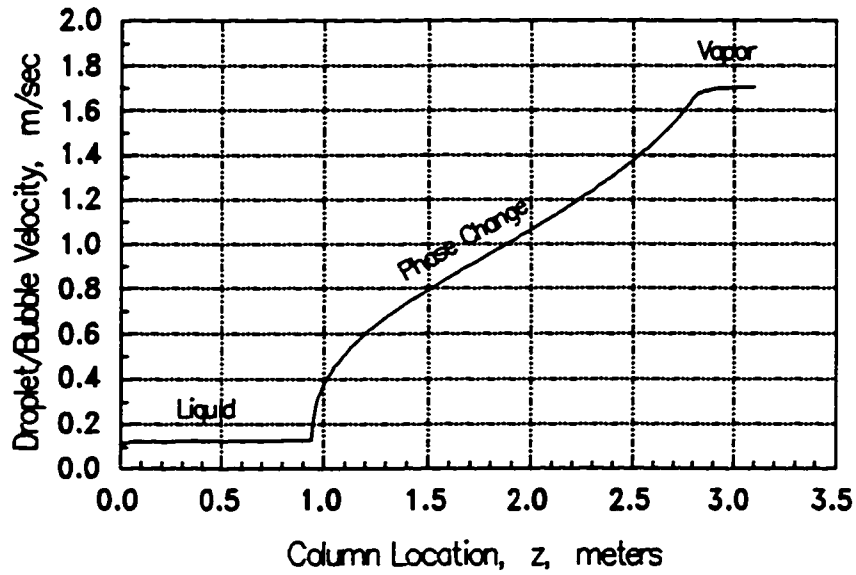
Figure 17 Droplet/Bubble Velocity Profile for Simulation Shown in Figure 8.
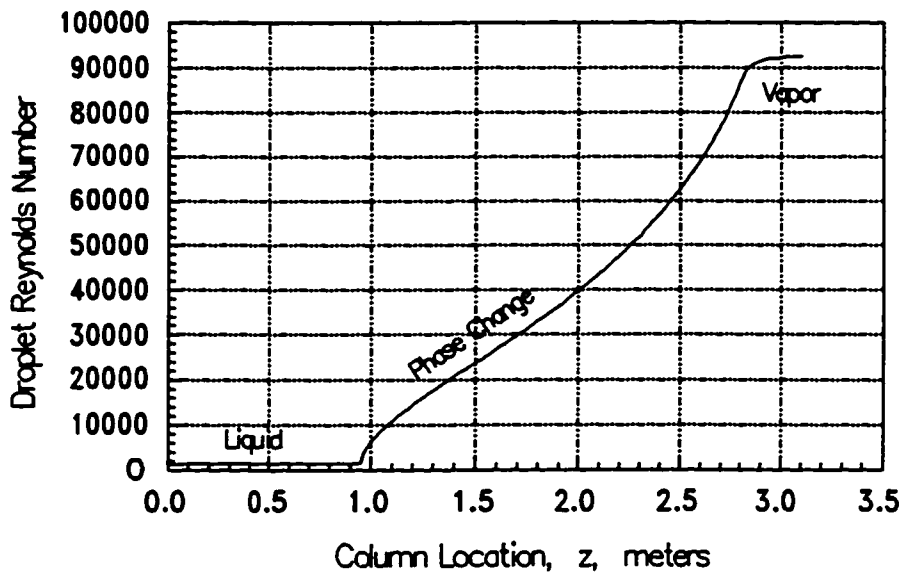
Figure 18 Droplet/Bubble Reynolds Number Profile for Simulation Shown in Figure 8.

Figures 13 and 14 show the droplet/bubble half opening angle and dispersed fluid quality. The profile clearly shows the progression from liquid to vapor through the phase change.

Figure 15 shows the holdup. As expected, this holdup is only a small fraction during the liquid rise. Upon vaporization, the void fraction increases dramatically. The importance of the holdup is, of course, its relationship to column flooding.

Figure 16 indicates the growth in the droplet/bubble radius. A comparison with Figures 13 and 14 reaffirms the progression through phase change from liquid to vapor, indicating a growth from 2 mm radius specified at injection to slightly more that 9 mm at completion of phase change.

Figures 17 and 18 depict droplet/bubble velocity and Reynolds number respectively. Like the previously depicted parameters, the increase in velocity at approximately the 1.0 meters location signals the onset of phase change with completion at 2.6 meters. Of note is the order of magnitude difference between the rise of the most of the parameters and that of the Reynolds number. This difference is attributed to the fact that a one-order increase in the velocity and droplet/bubble radius combines to a two-order of magnitudes increase in the Reynolds number.

The preceding profiles illustrate the potential for using simulation modeling for studying parameter behavior and trends. While it is acknowledged that experimental results are less challengeable, acquisition remains difficult and for

some parameters are still unachievable. Simulation allows for exploration of the effects by and on key parameters.

Parametric Sensitivities

The simulation model, like its experimental counterpart, functions on the input of eight key parameters. They are two fluid flow rates, two fluid inlet temperatures, dispersed fluid initial droplet/bubble radius, and three device parameters - length, radius and operating pressure. One could include the fluid types as an input since fluid selection inherently creates a variety of thermodynamic and thermophysical property combinations, bringing the list of key parameters to ten. Including fluid type creates considerably more variation since each fluid has a unique density-viscosity-conductivity-specific heat combination. In this work, the list is limited to the first eight parameters stated above.

Initial Droplet Radius

Control of the dispersed fluid droplet size at injection has a marked effect on DCHX performance. Figure 19 shows the effect of varying the initial droplet radius on the duty of a water/n-pentane system. Primarily, the influence is caused by the reduction in overall surface area for a given fluid flow rate. This is seen in a simple analysis of the surface area and volume formulae for a sphere. Surface area of an individual droplet increases proportionally with R^2, whereas droplet volume increases with R^3. A doubling of the radius results in four times as much surface area on a droplet (which might first appear to be good for heat transfer)

but results in one eighth the number of total droplets containing eight times as much of the fluid. The net result is a reduction in duty on the order of one half.
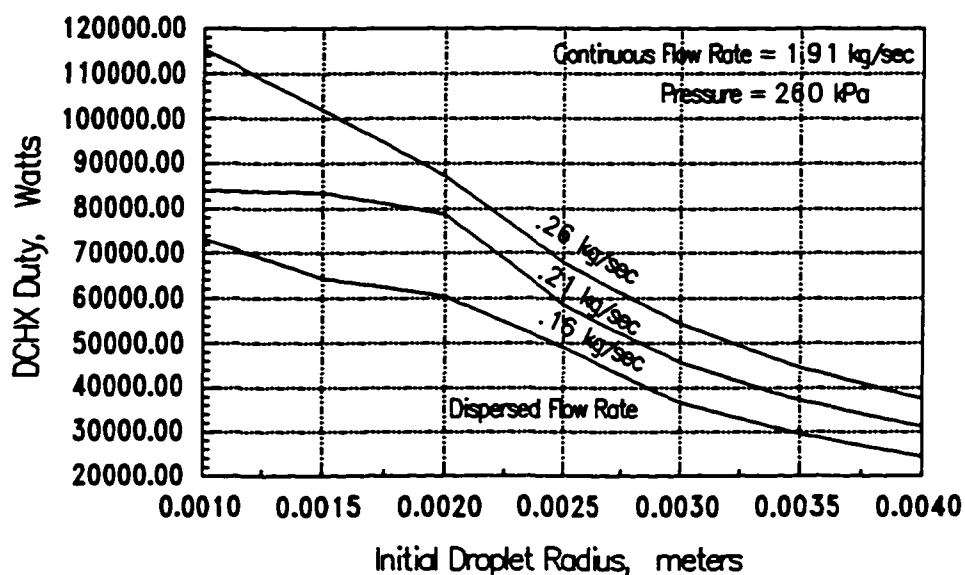
Figure 19 Sensitivity of DCHX Duty to Initial Droplet Radius.

Hydrodynamic factors associated with increasing or decreasing droplet size affect the duty as well. Larger droplets react to the viscosity of the counterflowing continuous fluid, causing a reduction in rise velocity. While this increases residence time in the DCHX, the more dominant influence is that convection processes are reduced, causing a loss of duty as droplet size increases.

A further compounding effect is that in a system where phase change barely finishes such as the examples shown in Figures 9 through 11, a reduction in heat transfer early on in dispersed fluid rise can result in incomplete vaporization

before the fluid exits. This causes an even larger loss of overall duty since a significant portion of the heat transfer occurs during the phase change.

Generally, it is desirable to have as small a droplet size as is practical at injection to generate the highest duty. The limitation to this is that small size droplets may be difficult to achieve if one desires a large dispersed flow rate. Nozzle construction is a key issue.

Column Length

The effects of column length on DCHX duty are less pronounced but no less interesting. Generally, longer columns result in higher duty. The principle reason is the increased residence time during which the fluids are in longer contact. A secondary factor is the change in hydrostatic pressure exerted on the fluid in the lower portion of the column. It is commonly known that system duty increases with increased operating pressure because of *better* fluid properties. Increased column length increases the pressure at the bottom of a column, where the dispersed fluid enters.

The trend in duty versus column length for a water/n-pentane two phase system is shown in Figure 20. Note that the increased duty is not linear but tapers off as column length passes a certain length. This is due to the dispersed droplets/bubbles completing vaporization at some length less than the total length of the column. In these cases, the fluid merely completes its travel to the top of the column exchanging little or no heat once it has vaporized and reached the continuous fluid's temperature. Figure 20 suggests that a given system has an

optimum length beyond which there is a diminishing return and which would

require a cost-duty tradeoff analysis.
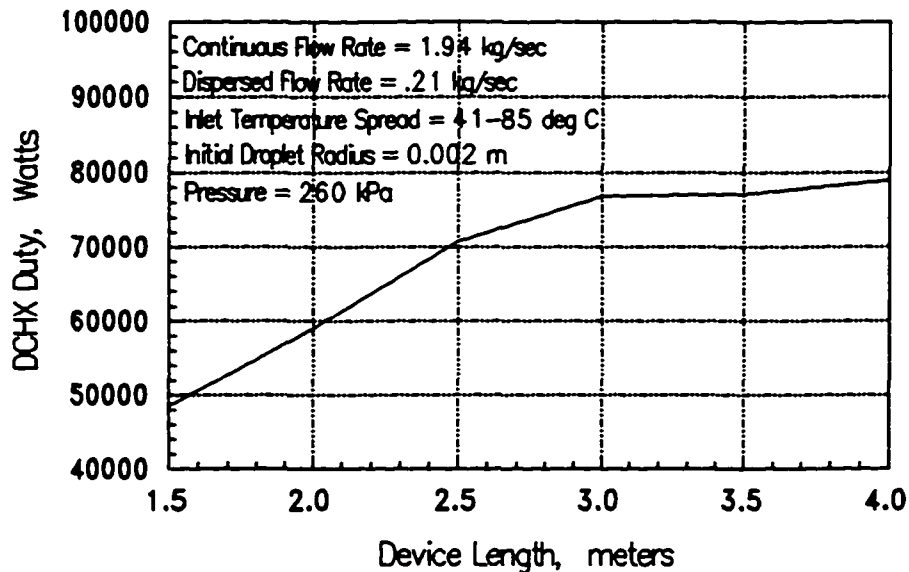
Figure 20 Sensitivity of DCHX Duty to Column Length.

Fluid Flow Rates

The most complex factors affecting DCHX performance are the individual

fluid flow rates and their inlet temperatures (discussed in the next section). As

mentioned in Chapter 1, control of fluid flow rates can be used to achieve one of

several desired outcomes - temperature control of one fluid or overall system duty.

A discussion of temperature control and optimized flow rates follows in later

sections. Here a discussion is made about the effect of flow rates on overall duty.

Figure 21 depicts the results of simulations over a range of dispersed and

continuous fluid flow rates in a water/n-pentane system. In general, the trend

follows that for a given flow rate of continuous fluid, the higher the
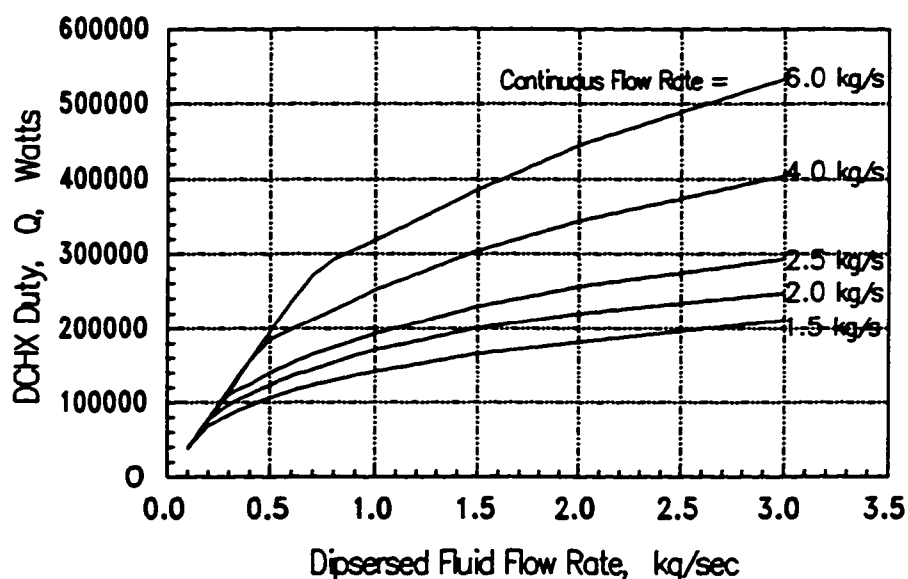
Figure 21 Sensitivity of DCHX Duty to Fluid Flow Rates.

dispersed fluid (n-pentane) flow rate is, the higher the duty is. However, it is seen

in the figure that the increase is not linear and duty tends to level off as the

dispersed flow increases. The reason for this is linked to the completion (or lack

of completion) of the phase change. Note that for flows ranging between

approximately 0.1 and 0.7 kg/sec, the rate of increase is nearly identical over the

range of reference continuous flow rates. The rise follows a particular gradient

until the duty breaks off of this gradient, fanning out to an asymptotic leveling.

The sharp coincidental rise at the lower dispersed flow rates corresponds with the

cases where phase change occurs and is completed. The point at which each

profile *breaks* off from this common gradient is the point at which phase change fails to complete. Since a large amount of the heat transfer occurs during the phase change, an incomplete change shows up quickly in a curbing of duty. The leveling off of duty is evident in each of the five referenced continuous fluid flow rates.

Dispersed fluid flow rates greater than the rate at which duty levels off have the effect of making the three-phase system appear more and more like one with only two phases. The higher flow rates require a higher extraction of heat during the preheating section, which elevates the location at which phase change begins. Given the relatively inflexible amount of time in which phase change occurs (Figures 9, 10, and 11), a delay in the onset of phase change directly results in the loss of some portion of the change. The higher the dispersed flow rate, the more of the change is lost. The system still experiences an increase of duty with increased dispersed flow rate but at a significantly reduced gradient. This suggests that any three phase system should be operated at or near the point at which the phase change process can adequately be completed. It should be noted that in the this an other analyses, flooding conditions (one fluid hydrodynamicially overpowering the other) were not addressed. While the coded model accounts for the condition when it occurs, tested ranges of parameters were all within *safe* operating conditions.

Inlet Temperature

An interesting aspect influencing DCHX performance is the fluids' inlet

temperatures and inlet temperature differential. It is noted, though, that this is an

aspect over which one often has no control. In geothermal applications, for

example, a system is restricted to using heated underground water which will be

fixed at some temperature determined by natural forces. If control is feasible, the

dispersed fluid should be introduced as close as possible to its vaporization

temperature. Figure 22 depicts the duty of the three phase water/n-pentane

system. Similar to Figure 20, a range of dispersed fluid flow
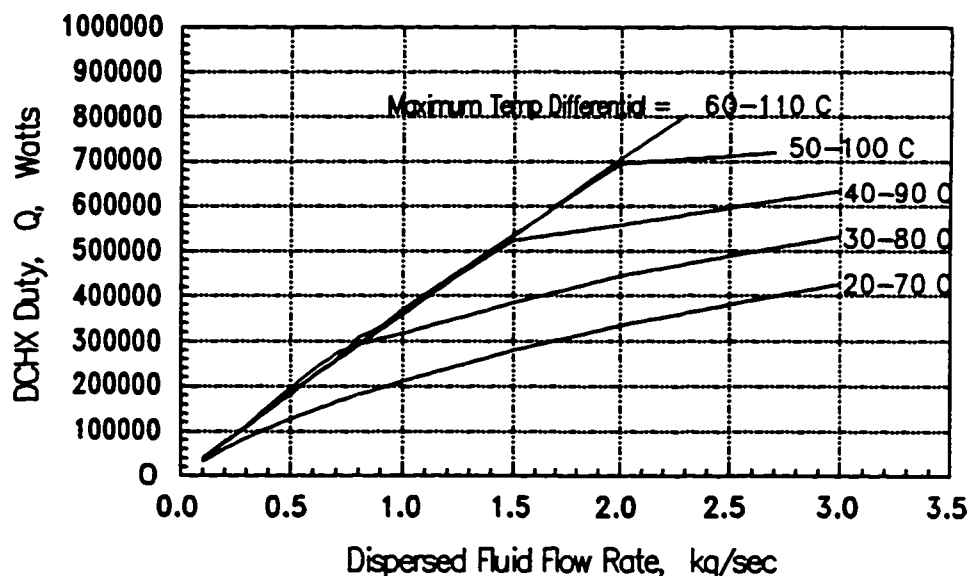
Figure 22 Sensitivity of DCHX Duty to Fluid Inlet Temperatures and Spread.

rates is examined against a reference set of temperatures. An overall inlet spread

of 50°C is maintained but distributed over a dispersed fluid inlet temperatures

range between 20° to 60°C and corresponding continuous fluid inlet temperatures

of 70° to 110°C. As in the flow rate effects discussed in the previous section, here

again there is a breaking off and fanning out of the duty curve. The trend is again attributed to the phase change portion. In the lower temperature spreads, the n-pentane spends an inordinate amount of time preheating before reaching vaporization. Vaporization temperature occurs at approximately 62°C for the operating pressure of 260 kPa used for this comparison. With a water inlet temperature of only 70°C, the dispersed fluid spends little time in the phase change portion. As the spread moves up to the last tested range of 60°-110°C condition, less and less time is spent preheating, resulting in more time spent in phase change. The result of this is the notable increase in duty shown in Figure 22.

Reversing Fluid Roles

A final aspect affecting DCHX performance is the selection of the roles the fluids take on in a system. Thus far, discussions have focused on n-pentane/water. Runs involving water and commercial heat transfer fluids or oils (examples of two-phase applications) show that duty can increase or decrease depending on whether the transfer fluids or oils are used as the dispersed or continuous fluid.

Table 2 lists the results of six cases where fluid combinations were tried and then their roles were reversed for comparison. It is seen that there is a mix of results ranging from as an increas of 37% to a loss of 47% in duty when the transfer fluids or oils were switched to the role of the continuous fluid. The apparent factor responsible is the fluids' viscosity ratio which affects droplet's velocity while in the system. Table 3 lists pertinent properties of the six transfer

fluids used in the test cases. All were similar except for viscosity and subsequently

the viscosity ratio with water. In the three cases where duty increased with

switching the transfer fluid to the continuous role, the fluid's viscosities were of

TABLE 1 Device Output as a Result of Reversing Roles of Fluids

Dispersed Fluid	Continuous Fluid	Total Device Output- W	
Syltherm® 800	H₂O	171,620	
H₂O	Syltherm® 800	235,420	37% Inc
Therminol® 44	H₂O	230,381	
H₂O	Therminol® 44	270,738	17% Inc
Transformer Oil	H₂O	223,526	
H₂O	Transformer Oil	228,428	2% Inc
TM-1 Oil	H₂O	202,753	
H₂O	TM-1 Oil	201,358	1% Dec
Therminol® 55	H₂O	246,286	
H₂O	Therminol® 55	219,785	11% Dec
MS-20 Oil	H₂O	260,889	
H₂O	MS-20 Oil	138,686	47% Dec

Notes
1. Flow rates are at optimum for fluid combination with H₂O inlet temperature at 22°C and transfer fluid/oil inlet temperature at 100°C, column length of 3.0 m, column radius of .5642 m, initial droplet radius of 2 mm, and operating pressure of 101.3 kPa.

TABLE 2 Approximate Fluid Properties in DCHX Application.

	Syltherm® 800	Therminol® 44	Transformer Oil
Density kg/m³	892	885	847
Viscosity Pa-s	.0008	.0018	.0060
Specific Heat J/kg-K	1701	2074	1939
Conductivity W/m-K	.1031	.1357	.1051
Fluid-H₂O Viscosity Ratio	1.18	2.83	9.23
	TM-1 Oil	Therminol® 55	MS-20 Oil
Density kg/m³	857	848	864
Viscosity Pa-s	.0048	.0123	.1120
Specific Heat J/kg-K	.1702	2100	2196
Conductivity W/m-K	.1139	.1234	.1305
Fluid-Water Viscosity Ratio	7.35	18.92	172.1

approximately the same magnitude as that of the water, having ratios ranging from 1.18 to 9.23. In the three cases where duty decreased the fluids were significantly more viscous than water having a fluid-to-water visocity ratio ranging from 7.35 to 172.1. The conclusion drawn from this is that the less viscous fluid should be brought in as the continuous fluid. The reason is that the less viscous the continuous fluid, the higher the droplet rise velocity which results in higher convection. Some overlap of the trend is seen in the two marginally close cases of transformer oil/water and TM-1 oil/water, suggesting that the pivoting value of viscosity ratio lies approximately in the 7.0 to 10.0 range. Fluid combinations falling in this range would have to be examined individually to determine the best selection of roles.

Dual Utility Optimization

The discussion in Chapter 1 on DCHX optimization highlighted that various forms of optimization exist for DCHX. A system may be optimized for maximum duty, target temperature, or dual utility of fluids. To maximize on the first two, one need only supply an ample amount of flow of the non-critical fluid (the fluid of non-limited supply) for maximum duty or iterate on the flow rate until a specific target temperature in the fluid temperature profile is achieved. The third method requires the use of the Dual Utility Optimization characteristic presented in Chapter 2.

As highlighted in Chapter 1, classical measures such as the LMTD and effectiveness can fail to identify when optimized flow rates are achieved. Figures

23, 24, and 25 demonstrate this failure and show that the use of the DUO

characteristic achieves the desired outcome. Figures 23 and 24 depict the behavior

of the DUO characteristic when device length and dispersed droplet radius are

varied over a range of values in a two-phase liquid-liquid DCHX using water and

Therminol-44® - a commercially produced heat transfer fluid. In these two

particular cases, the DUO correlates closely with the traditional definition of

effectiveness. Reliance on classical effectiveness would be sufficient if length and

droplet radius were the only unknown parameters.
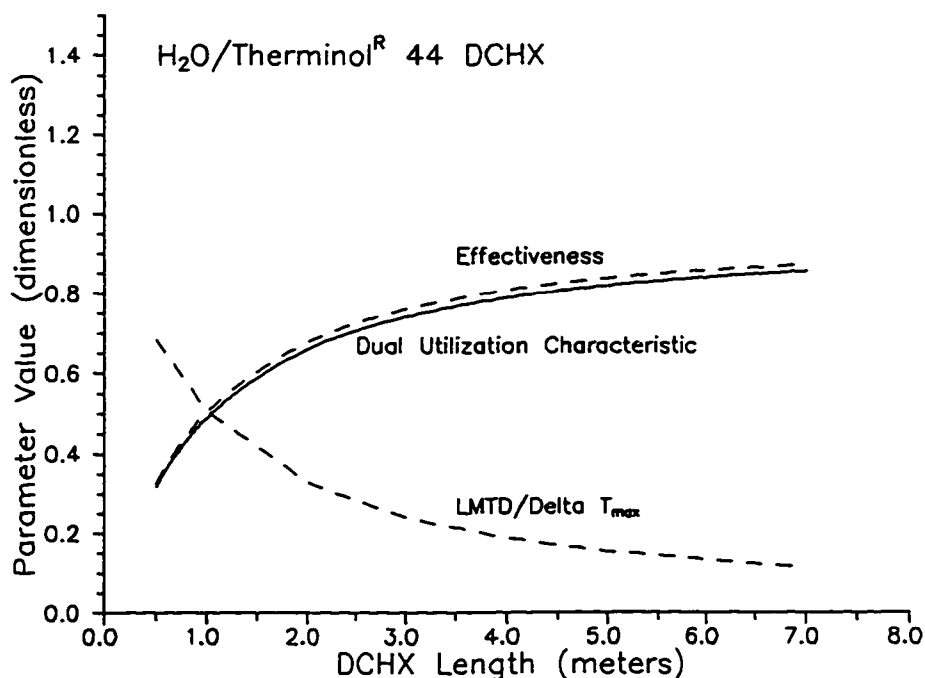
Figure 23 Comparison of Dual Utility Indicator to Effectiveness and
LMTD as a Sensitivity Indicator for Column Length.
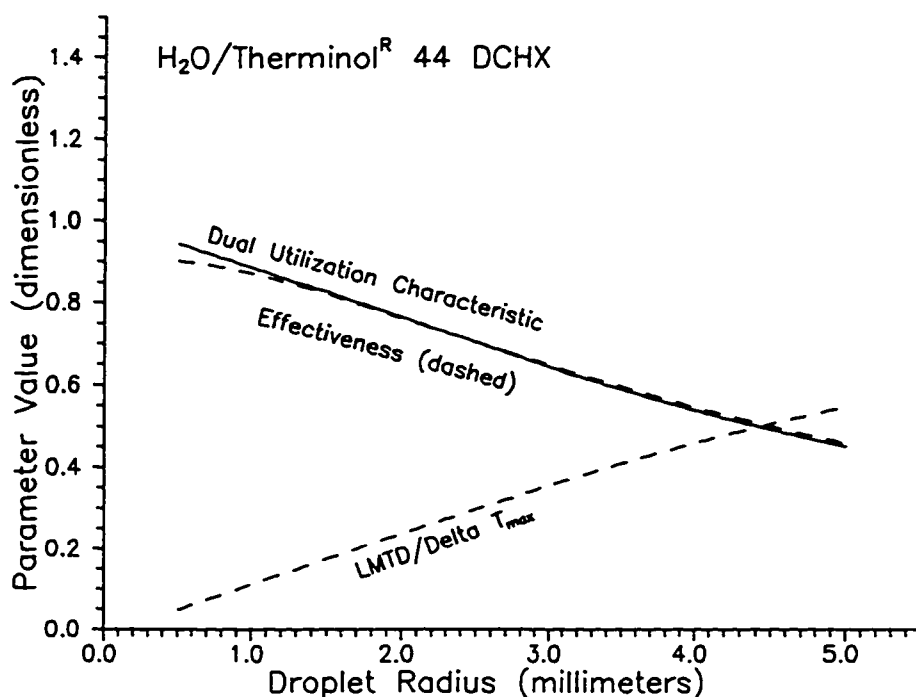
Figure 24 Comparison of Dual Utility Indicator to Effectiveness and LMTD as a Sensitivity Indicator for Initial Droplet Radius.

A more complex situation develops when the parameter in question is fluid flow rate as Figure 25 illustrates. It is noted that variations in device length and droplet radius are not linked to the dual utility problem per se but rather to the maximum duty output. For dual utility, properly balanced flow rates are required. Figure 25 shows differing trends in the profiles for the classical LMTD and effectiveness measures and based on effectiveness alone, one would conclude that an unoptimized condition occurred at a continuous fluid (water) flow rate of approximately 1.0 kg/sec in the evaluated system.
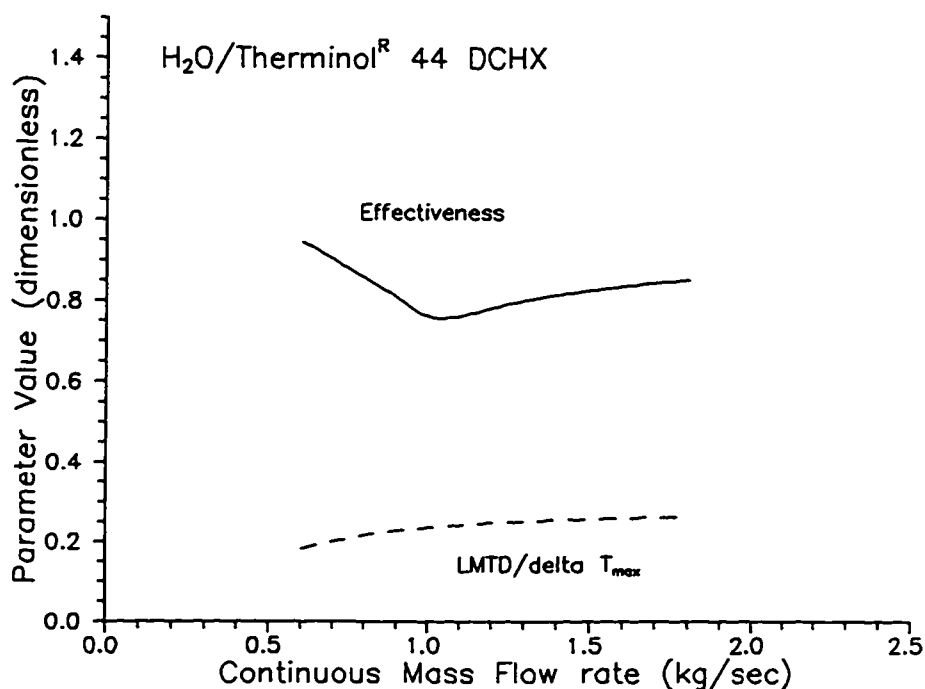
Figure 25 Effectiveness and LMTD Sensitivity to Continuous Fluid Flow Rate. Dispersed Fluid Flow Rate = 2.0 Kg/Sec.

In Figure 26, a plot of the DUO characteristic is added. The result reveals that an optimized condition is reached at the 1.0 kg/sec flow rate. In reaching a peak, the measure indicates that for the referenced flow rate of 2.0 kg/sec of heat transfer fluid, a 1.0 kg/sec flow rate of water will yield temperature profiles that are both parallel and at as close of an approach as is possible for the given inlet temperatures, droplet radii, length, etc., specified for this system. This is confirmed by examining the resulting fluid temperature profiles shown in Figure 27. By using the developed DUO characteristic indicator, the dual utility condition can be found for two-phase systems.
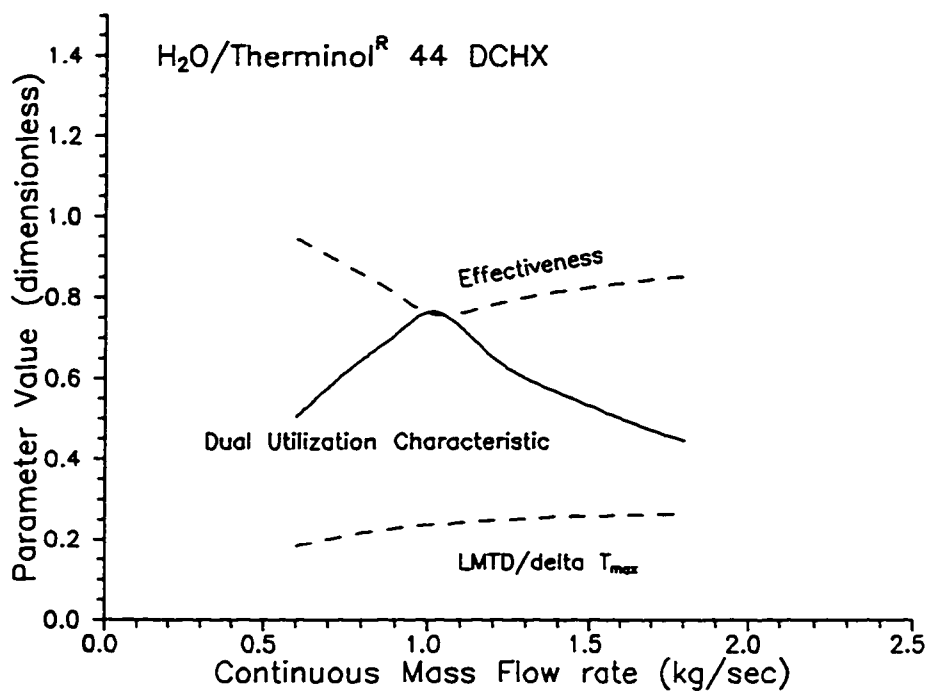
Figure 26 Comparison of Dual Utility Indicator to Effectiveness and LMTD as a Sensitivity Indicator for Continuous Fluid Flow Rate.
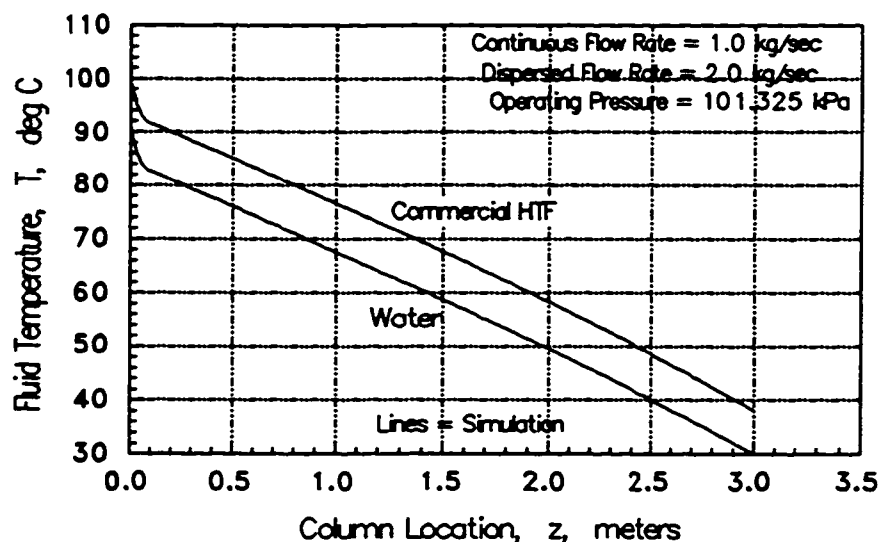
Figure 27 Temperature Profile for Liquid-Liquid DCHX Optimized for Dual Utility.

Referencing the correlation of Figure 23 and the stated observation that

device length is generally unrelated to the dual utility condition, Figure 28 is

presented, confirming that the optimized dual utility flow rates are unaffected by

device length. The peak in the DUO indicator remains fixed at the 1.0 kg/sec rate.

Device length has the overall effect of improving on the situation - bringing the

profiles even closer - once the proper balance is found. In effect, the DUO

exclusively identifies the flow rate balance and then can be used to fine tune other

parameters.
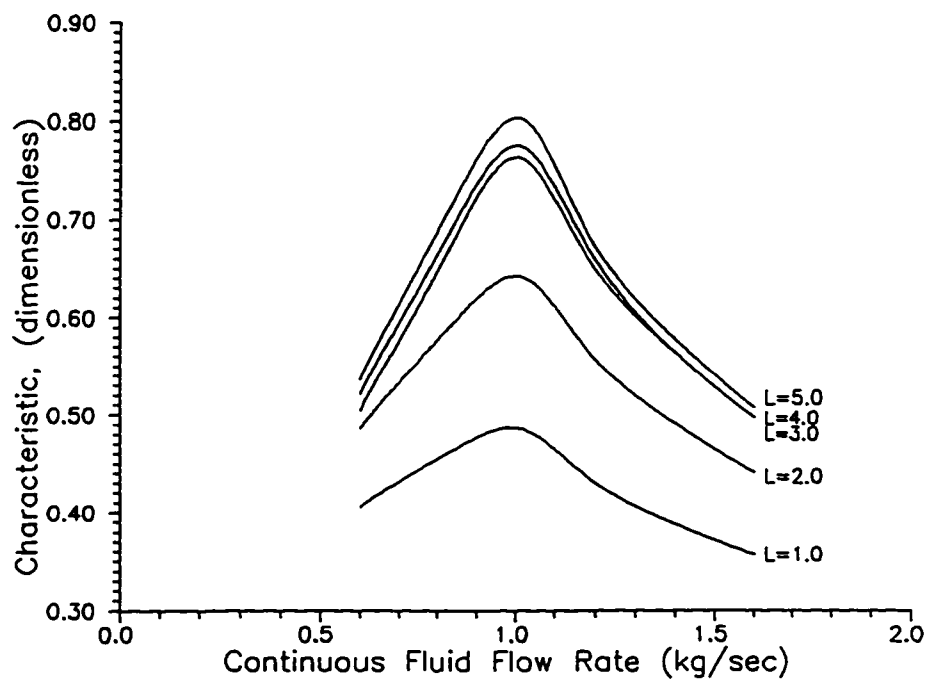
Figure 28 Combined Effects of Balanced Flow Rate and DCHX Length
on Dual Utility Optimization. (1.0 m ≤ DCHX Length ≤ 5.0 m)

Simulation Based Designs for a Gas-Fired, Direct-Contact Water Heater

The practicality of the one-dimensional simulation was tested by employing the model to design a DCHX for industrial water heating. The designs focused on dispersing exhaust gases from the combustion of natural gas in air through a flow of water at tap temperature. Direct contact between the exhaust gases and water would cause the water to heat up according the flows being supplied. Using the model to test variations on two types of candidate systems resulted in designs which were presented at an international conference. Synopses of the designs are given in Appendix III which condenses formally published work (Brickman, Sethi and Boehm, 1994).

A secondary purpose of employing the model for the designs was to test its useability by a person not as familiar with direct-contact processes. Encoding the input file proved to be a reasonably simple task as did interpreting ensuing results. The model was used in an interactive fashion, with the non-expert subject (second author of the cited paper) testing and improving best guess parameters. The final designs were arrived upon following a thorough exploration of parameter variations. It was generally felt that the program was built at the right level of knowledge that would be expected of field engineers.

Two-Dimensional Sieve Tray Analysis

Two-dimensional modelling is useful in analyzing one particular form of DCHX enhancement, namely the addition of sieve trays in the preheating section. While fully two-dimensional modelling of an entire DCHX configured with half a dozen or more trays would be formidable, the modelling of a single module (the space between two consecutive trays) is more readily accomplished with results offering insight to the sieve tray enhancement.

The primary mechanism at work in sieve tray enhancement is the increased convection due to increased relative flow of continuous fluid around the droplets, resulting in a higher heat transfer for a given length of the DCHX. Increased relative flow is achieved by increasing the nominal continuous fluid input flow and forcing it through alternating by-pass gaps on the sides of a tray. This creates a cross flow through which the droplet must rise. The cross flow adds a horizontal velocity component, resulting in a higher relative flow around the droplets. It should be noted that forcing the flow to *switchback* through an array of properly sized and spaced trays is crucial to the enhancement as increasing the continuous flow rate has negligible effect by itself in an unmodified column.

Convection around an individual droplet is calculated from the stable rise expressions (characteristic of the preheating section) given in Chapter 2 since sieve trays are intended for use in preheating. If consecutive sieve trays are placed in the flow with alternating by-pass gaps, a cross flow is created in the continuous fluid. Dispersed fluid droplets enter this module through perforations in the sieve

tray and rise up through the cross flow, are swept in the direction of the cross flow and caught under the next higher tray. The degree to which droplets are swept sideways depends primarily on the continuous fluid flow rate and to a lesser degree on the size of the by-pass gap and vertical spacing of the trays. At typical continuous fluid (water) flow rates, the hydrodynamic flow field can be approximately considered to be a potential flow field with minimal influence by the boundary influence. This assumption is defended by the fact that the bulk of interest lies in the heat transfer aspects of droplets in the field and not the micro analysis of an individual droplet's path in or out of a boundary layer.

The two-dimensional flow field is found by numerical application of the expressions described in Chapter 2. The result is an output grid of horizontal and vertical velocities. For each droplet starting position, a path is traced by the application of simple law of motion. With the paths known, a final iteration is made to determine droplet heat transfer referencing the changing velocity pattern of the two-dimensional space. From this, droplet efficiencies are calculated. It is found that a wide range of droplet patterns result when the continuous fluid flow rates are varied in a tray module.

Figures 29 through 35 show droplet traces through a sieve tray module with an aspect ratio of 0.5 and a by-pass gap of 20% of the column's cross sectional opening of 0.61 meters (column diameter). As stated in Chapter 2, grid spacing for the field was 20 x 20 and for the flow rates tested, boundary layer effects were did not appear. The reference continuous flow rate was 1.91 kg/sec. Figure 29

shows the result of the flow passing through one set of sieve trays. It is seen that there is little effect on a droplet's horizontal path due to the continuous flow being constricted through the by-pass gap. Generally, the droplet's vertical velocity remains constant except near the by-pass gap, where there is a slowing of the droplet. Note that Figure 29 shows a droplet being released in the lower by-pass gap. This trace is included to illustrate that a droplet reaching that location from the module just below would continue on up through the restriction into the module. This is an approximate continuation of the first trace on the left.

The effects of the cross flow become more apparent when the flow rate is increased in multiples. Figures 30 through 35 show droplet traces when the continuous flow rate is doubled, tripled, etc. Of interest are the runs which show traces for flow rates multiplied by 2, 3, 4, 5, and 6, respectively. In each succeeding run, more and more side sweep appears. In the latter runs, there is a significant amount of *capturing* of the droplets released near the exiting by-pass gap. The run shown in Figure 35 (10x reference rate) is presented to illustrate an extreme case where there is an inordinately high amount of capture, a condition that would be undesirable.
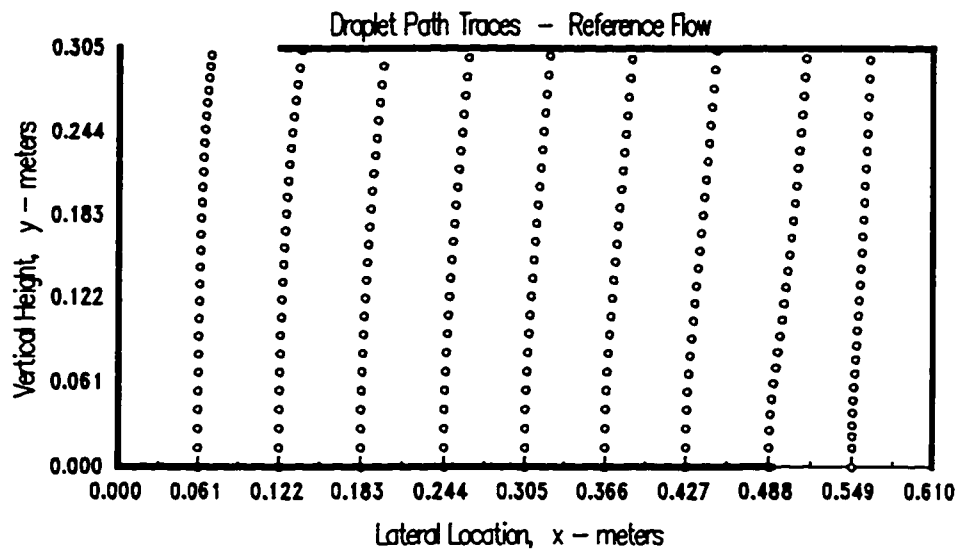
Figure 29 Droplet Path Traces - n-Pentane/H₂O. Reference Continuous Flow Rate = 1.91 kg/sec, Droplet Radius = 2 mm.
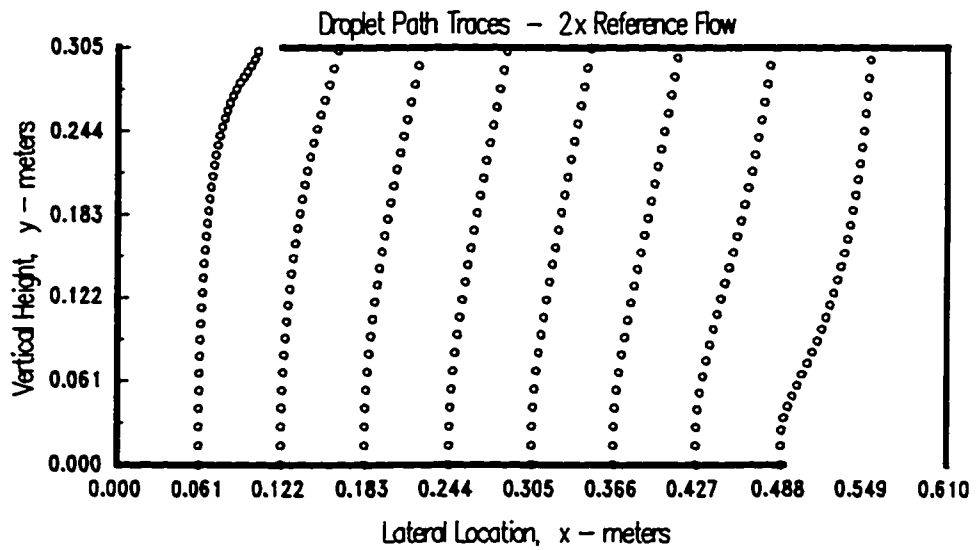
Figure 30 Droplet Path Traces - n-Pentane/H₂O. Continuous Flow Field Velocities = 2 x Reference, Droplet Radius = 2 mm.
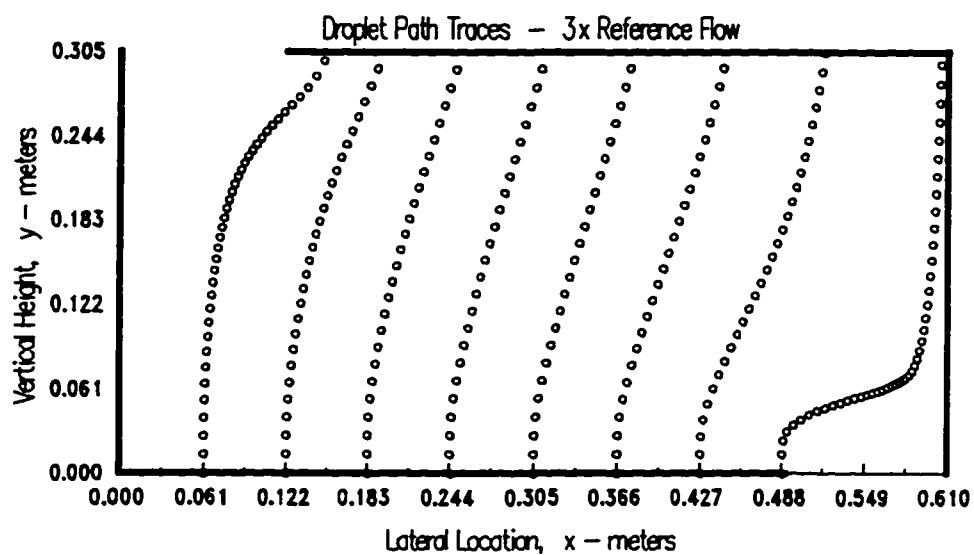
Figure 31 Droplet Path Traces - n-Pentane/H_2O. Continuous Flow Field Velocities = 3 x Reference, Droplet Radius = 2 mm.
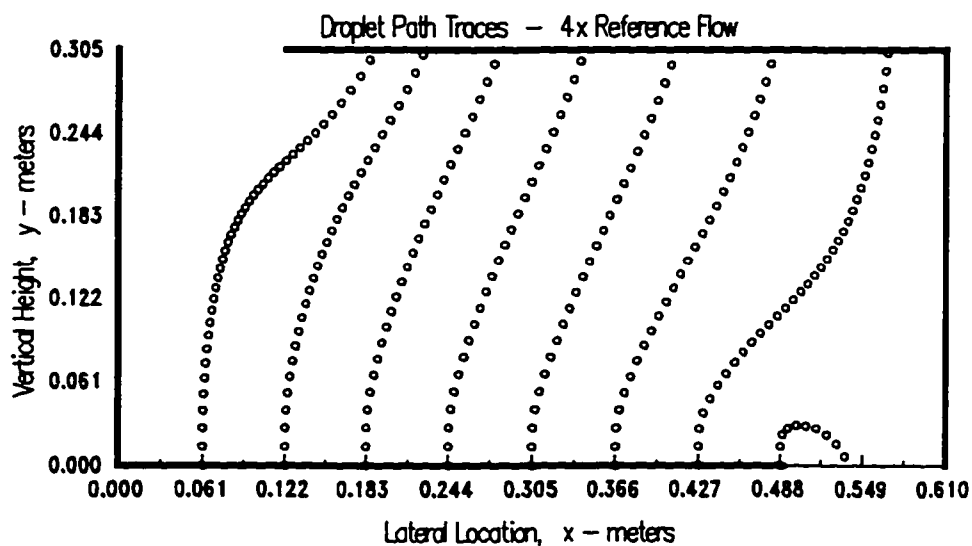
Figure 32 Droplet Path Traces - n-Pentane/H_2O. Continuous Flow Field Velocities = 4 x Reference, Droplet Radius = 2 mm.
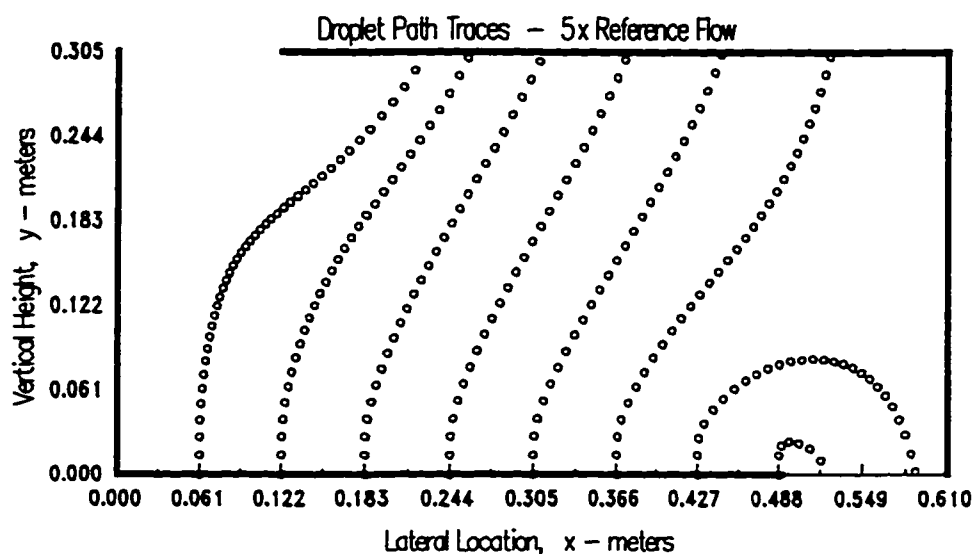
Figure 33 Droplet Path Traces - n-Pentane/H_2O. Continuous Flow Field Velocities = 5 x Reference, Droplet Radius = 2 mm.
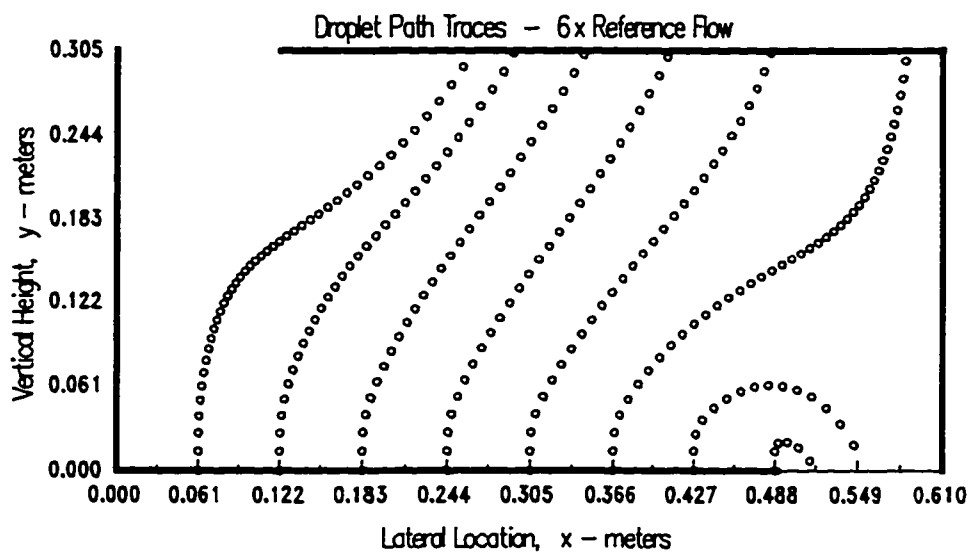
Figure 34 Droplet Path Traces - n-Pentane/H_2O. Continuous Flow Field Velocities = 6 x Reference, Droplet Radius = 2 mm.
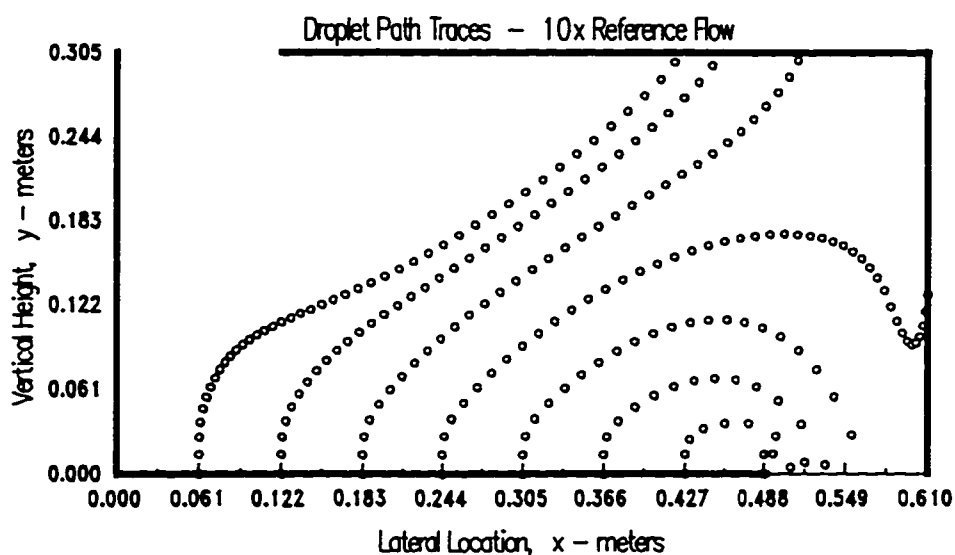
Figure 35 Droplet Path Traces - n-Pentane/H_2O. Continuous Flow Field Velocities = 10 x Reference, Droplet Radius = 2 mm.

As stated, the flow field and path traces allow for the calculation of heat transfer to a droplet due to a continuously updated relative velocity vector. The heat gained - evidenced by the droplets rise in temperature - is compared to the maximum gain possible in the module, and a droplet efficiency is found. Figure 36 shows efficiencies for individual droplet traces referenced to their release location on the lower tray. The figure shows an increase in efficiency as the flow rate is increased and that the highest gain is found in the traces closest to the by-pass gap where, as one would expect, the flow is locally contracting or expanding. Note the sharp fall off in efficiency for trace locations near the lower by-pass gap. The efficiencies of these traces are calculated to show the loss resulting from a droplet being captured by the continuous flow and being swept under the lower tray.

Effect of Continuous Flow Rate on Heat Transfer Efficiency
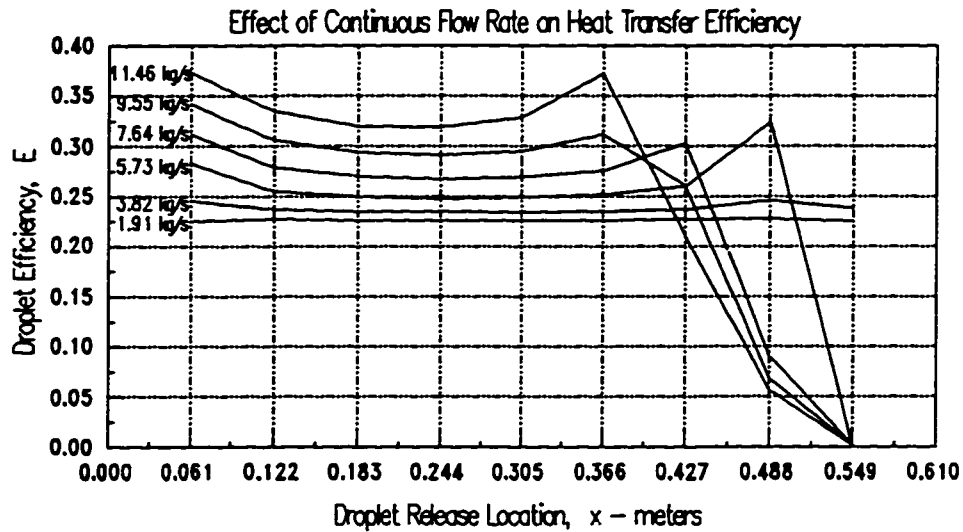
Figure 36 Droplet Effectiveness as a Function of Release Location and Continuous Flow Rate.

Droplet efficiency can be averaged for those traces that traverse the module without capture. These averages are plotted to reveal the benefit of creating the cross flow condition by sieve tray. Figure 37 shows that the average efficiency can be raised from approximately .22 to .35. This improvement is attributed to two factors - (1) the increased relative flow past the droplet due to the establishment of a cross flow and (2) the increase residence time particularly noticeable in the traces rising from the ends of the lower tray which experience a greater vertical component. The latter accounts for the saddle shape of the curves in Figure 36.

The saddle shape of Figure 36 suggests a design consideration for constructing sieve trays. Perforations made in the trays could be of greater density at the edges to exploit the higher local efficiency of these locations. Further it is seen that trays should have a non-perforated margin along the edge that protrudes into the flow to prevent droplet capture by the flow at this location.
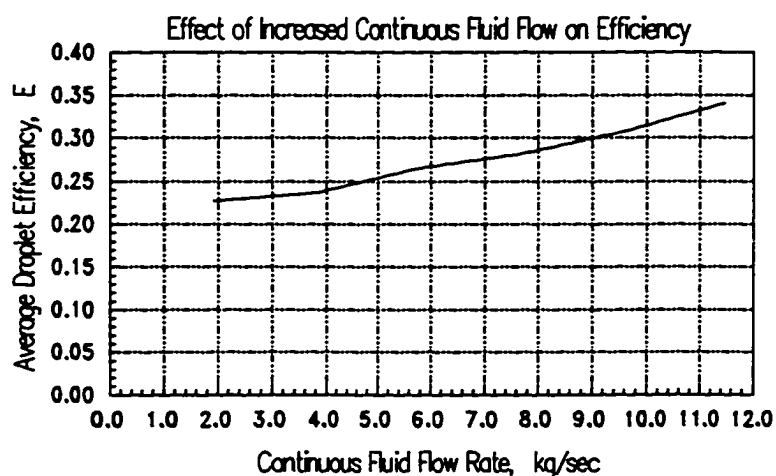
Figure 37 Effect of Continuous Flow Rate on Average Droplet Efficiency. (Only droplets traversing module are included in average.)

An alternate use of sieve trays is the strategic placement of a single tray for the purpose of droplet size control. As discussed earlier in this chapter, droplet size, volume, and population greatly affect the heat transfer. Reducing the size (radius) of droplet a factor of two creates a population four times as large, thus increasing the heat transfer.

A scenario for this approach differs from the two-dimensional analysis just presented. There is negligible droplet growth during the preheating stage of a three-phase system when the dispersed fluid is in liquid form. Bubble growth occurs during phase change, so the first consideration is the placement of the tray at a physical location in that region. If, in a particular application in which nominal liquid droplet radius was 2.0 mm and vapor bubble growth was from 2.0 mm to 9.0 mm, one wished to reset the growing bubble back to a 2.0 mm bubble when it reached a interim size of 5.0, the key question would be where to place the tray. Once a tray is positioned and the steady state heat transfer profile changes, the effect cascades through the entire column altering the preheating time and shifting the column location where vaporization (and bubble growth) begins. The result is that tray placement based on a unmodified column is no longer correct and a new location must be tried and revaluated, which leads to an experimentally endless process.

Numerically, tray placement is a substantially easier process. The simulation code can be modified to search for the placement compatible with the specified boundary and initial conditions. Figures 38 and 39 show comparisons of the heat transfer and droplet/bubble radius for an open spray column and one configured with a single sieve tray. The boost in heat transfer is quite evident at the 2.0 meter location in Figure 39 and corresponds to the resetting of the droplet size from 5.0 mm to 2.0 mm in Figure 39 and the accompanying increase in bubble population.
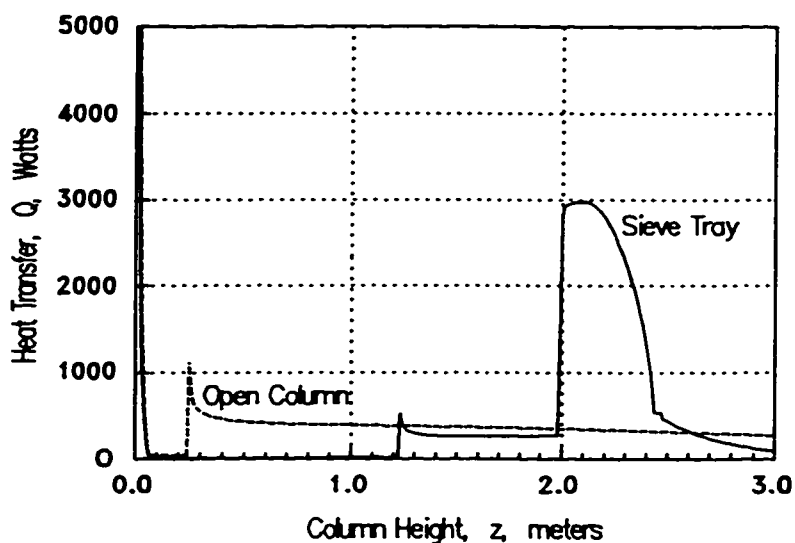
Figure 38 Comparison of Column-Wise Heat Transfer Between an Open Spray-Column and the Addition of a Single Sieve Tray Located in Vapor Rise Section of DCHX.
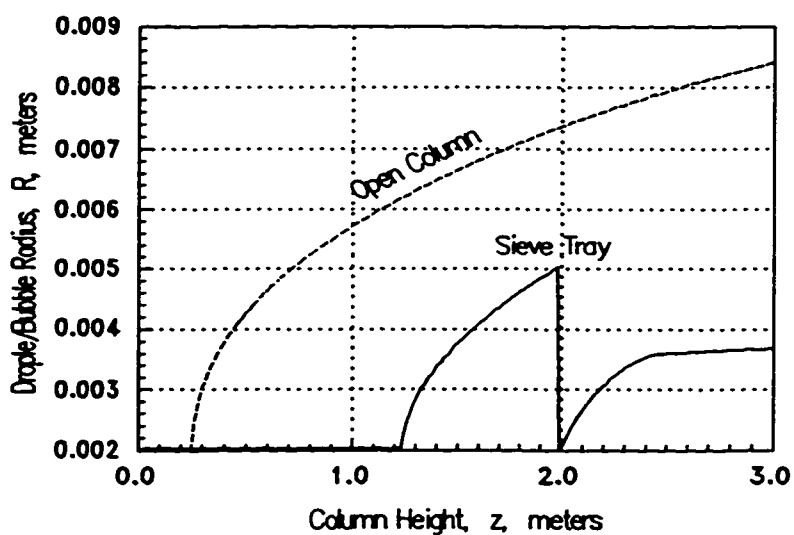
Figure 39 Effect of Radius Control by a Single Sieve Tray in Vapor Rise Section of DCHX.

It is seen in Figure 39 that bubble growth began at approximately 0.25

meters in the 3.0 meter column and that a bubble size of 5.0 mm was reached at

approximately 0.8 meters. However, droplet growth appears quite different in a

modified column, with onset of vaporization delayed until 1.2 meters and a 5.0 mm

bubble reached at 2.0 meters. The large extraction of heat associated with the

resetting of the bubble size reduces the continuous fluid temperature downstream,

which in turn slows the preheating time. This causes the shift in events in the

profiles, illustrating the synergism of DCHX system.

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

A robust one-dimensional model simulating the responses in a spray-column direct-contact heat exchanger is developed. The model represents a significant improvement over previous modelling works in that it incorporates an array of heat transfer expressions that account for the varying droplet/bubble regimes. The model also incorporates improvements that correct apparent errors in previous modelling. Comparisons are made to a limited amount of experimental data and parametric sensitivities are explored as a means of validating the work. Generally, there is good agreement with known data, suggesting a qualitative model that approaches quantitative status.

A method for determining a specific form of system optimization - dual utility - is presented. The success in determining optimization depends on the use of a new indicator developed in this work. The dual utility optimization (DUO) indicator is shown to be uniquely effective in identifying properly balanced flow rates, column dimensions, etc.

One-dimensional mechanisms are expanded into an analysis of sieve tray enhancement. By determining the two-dimensional flow field that would result from adding sieve trays on alternate sides of a column, the influence of cross flow

on droplets is examined and found to increase heat transfer efficiency due to increased relative flow around an individual droplet. An improvement on the order of 40% is possible by increasing the continuous fluid flow rate in a cross flow field by a factor of five. The key element is shown to be the cross flow, since increasing flow rate in an unmodified column has markedly less influence.

Findings of this work add to the understanding of this type of heat exchanger. Key elements are as follows.

1. It is critical to the modelling that each of the regimes that droplets/bubbles experience be separately modelled to insure accuracy and faithfulness to the physics of the system. Such a treatise of the regimes has not been found in other modelling attempts.

2. Parametric sensitivities reveal that when using dispersed fluids that will undergo phase change, significant increases in system duty are achieved by introducing the dispersed fluid at or near its boiling temperature. Whether or not this is possible without some kind of artificial preheating must be evaluated for each application. Gains on the order of 100% are shown possible by properly introducing a dispersed fluid near its boiling temperature vis a vis some lower amount.

3. It has traditionally been held that increasing flow rates increases system duty. This trend is supported in this work but suggests that the rate of duty increase is not linear with fluid flow rates but rather tapers off. For design, this tapering off must be evaluated against the cost (i.e. pumping costs) of increased

flow rates.

4. One form of optimization is now readily identified through the development of a customized indicator that identifies when two fluids are being equally utilized. This ability is of benefit when both working fluids are in limited supply or costs of supplying the fluids is a factor.

5. The addition of sieve trays to enhance the preheating portion of a DCHX can improve droplet heat transfer efficiency when accompanied by increased continuous fluid flow rate. The increased relative flow around a droplet increases convection, which improves heat transfer efficiency of a droplet over a given distance.

6. Selective use of a sieve tray in the vapor bubble rise portion as a means to control (reduce) bubble size is effective but has a cascading effect on the heat transfer profile of a DCHX column. Bubble size reduction creates more surface area due to a larger number of bubbles. A heat transfer *burst* occurs as a result. However, this burst lowers the temperature profile of the continuous fluid downstream, resulting in longer preheating time.

Direct-contact mechanisms are complex, and continued research would be beneficial. The following areas are suggested.

1. Continued research in droplet/bubble heat transfer is needed to develop either additional expressions or a single more universally applicable expression for determining droplet convection in a wider range of fluids (Prandtl numbers), temperatures, and Reynolds numbers . Existing expressions are still somewhat

restrictive or are unproven over wide ranging conditions.

2. Further work in optimization should be pursued, especially a study of the influence of switching the roles of the fluids. A cursory examination using the one-dimensional model revealed that in some cases simply switching the continuous fluid to the dispersed increased duty, though this was not a consistent event. It is suspected that a link exists between system duty and a mix of the fluids' viscosity ratio and thermophysical properties. Rise velocity directly affects convection around the droplet, and a correlation may be found to help determine which fluid should be dispersed into the other.

3. Expanded two-dimensional work to include extension to whole system modeling and alternate forms of enhancements such as packed beds, agitators, etc. should be pursued. Novel approaches must be found to prevent the tedious and computationally expensive task of individual droplet tracking. Both experimental and computational pursuits are required for validation and completeness. It is known that enhancements are of benefit, but defining useful expressions is needed if these types of heat exchangers are to see increased use.

4. An inevitable area of research will be injection nozzle design since as stated in the literature, injection circulation is a key regime in the heat transfer process. Since a number of injection methods are possible, increasing the knowledge base in this area will be important in eventual designs.

APPENDIX I

DEVELOPMENT OF VAPOR BUBBLE RISE REGIME
HEAT TRANSFER COEFFICIENT

Following a similar analysis as that of Coban and Boehm (1986), an

expression for the heat transfer coefficient for the vapor bubble rise regime is

found. The development differs from the Coban and Boehm work in that an

alternative expression from Carslaw & Jaeger (1959) is used as a starting point.

This alternative start expresses the temperature profile of a sphere due to heat

transfer from a *linearly varying continuous medium* as opposed to the expression

chosen by Coban and Boehm, which assumes a linearly changing surface

temperature. It will is shown that ending results are similar for the cases where

internal conduction resistance is much greater than the convective resistance but

that the new result will also work for those few cases where this condition is not

true. This analysis begins with the Carslaw & Jaeger expression for the

temperature profile inside a sphere exposed to a linearly changing continuous

fluid.

$$T(r, t) = \gamma \left[t + \frac{r^2 RH - R^2 (2 + RH)}{6 \alpha RH} \right]$$

$$+ \frac{2 R^2 H \gamma}{\alpha r} \sum_{n=1}^{\infty} \frac{e^{-\alpha \lambda_n^2 t} \sin r \lambda_n}{\lambda_n^2 \{R^2 \lambda_n^2 + RH(RH-1)\} \sin R \lambda_n} \qquad \text{I-1}$$

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Neglecting the oscillatory transient portion

$$T(r, t) = \gamma\left[t + \frac{r^2 RH - R^2(2+RH)}{6\alpha RH}\right]$$

I-2

Of particular note are the terms, H and γ, in the above expression. The Carslaw and Jaeger reference defines H as the ratio of the exterior convection coefficient to the conduction coefficient of the vapor inside the bubble or h_o/k_v. γ is the coefficient of the time variable describing the linearly changing temperature of the medium surrounding the bubble. While it is important, γ will be eliminated in the final steps of the development. Other terms of note are α ($k/\rho c_p$), the well known thermal diffusion coefficient, R, the physical radius of the bubble, and lower case r, the radial location variable for the sphere. The reader is directed to Carslaw and Jaeger for a complete description of the terms contained in the transient portion of equation I-1. No detail is given since this portion is dropped in this analysis.

The development is continued by finding the average interior temperature for use in a transfer relation. The average is used because it is assumed that a bubble will be sufficiently small and exhibit some mixing and thus will be of homogeneous temperature. The average is found by

$$T_{ave} = \frac{\int_{vol} T(r, t)\, dV}{V} = \frac{\int_0^R \gamma\left[t + \frac{r^2 RH - R^2(2+RH)}{6\alpha RH}\right] 4\pi r^2\, dr}{\frac{4}{3}\pi R^3}$$

I-3

which reduces to

$$T_{avo} = \gamma\left[t - \frac{R}{3\alpha H} - \frac{R^2}{15\alpha}\right] \qquad \text{I-4}$$

A temperature differential for use in a *total* convective expression for the bubble is found by

$$\Delta T = T_c - T_{avo} = \gamma t - \gamma\left[t - \frac{R}{3\alpha H} - \frac{R^2}{15\alpha}\right] = \gamma\left[\frac{R}{3\alpha H} + \frac{R^2}{15\alpha}\right] \qquad \text{I-5}$$

The temperature gradient at the bubble's surface is derived from equation I-2. The gradient is used to set up a conduction expression at the surface.

$$\frac{dT}{dr}\Big|_R = \gamma\left[\frac{r}{3\alpha}\right]_R = \frac{\gamma R}{3\alpha} \qquad \text{I-6}$$

A relationship is now established, equating the surface conduction into the sphere to the overall transfer into the interior of the sphere by convection. (Note the implication made that the heat transfer process is steady state, confirmed by the elimination of the time variable from the gradient and differential expressions. This relationship is

$$\dot{Q} = k_v A_B \frac{dT}{dr}\Big|_R = h_B A_B \Delta T \qquad \text{I-7}$$

or

$$\dot{Q} = k_v A_B \frac{\gamma R}{3\alpha} = h_B A_B \gamma\left[\frac{R}{3\alpha\frac{h_o}{k_v}} + \frac{R^2}{15\alpha}\right] \qquad \text{I-8}$$

Thus an expression for the overall transfer coefficient which accounts for the outside convection and interior conduction of a bubble in the vapor bubble rise regime, h_{vbr} (h_B in the above expression), can be defined as

$$h_{vbr} = \frac{5h_o k_v}{5k_v + Rh_o}$$ I-9

This expression is similar to the expression used by Coban and Boehm in that it represents the series combination of the exterior convection resistance and the internal conduction resistance. By noting that a separation of terms yields

$$h_{vbr} = \left[\frac{1}{h_o} + \frac{R}{5k_v}\right]^{-1}$$ I-10

the individual resistances are revealed. The last term is the same "*internal convection*" term derived by Coban and Boehm.

The h_o term is the convection coefficient acting between the continuous medium and the exterior surface of the bubble. A suitable expression for this term is described in Chapter 2.

It is of note to observe that if $5k_v/R << h_o$, then the heat transfer will be dominated by the $5k_v/R$ term

$$h_{vbr} = \frac{5k_v}{R} \; ; \quad \left(\frac{5k_v}{R} << h_o\right)$$ I-11

which is the Coban and Boehm result. In selecting the alternative starting

expression, a result is reached which essentially duplicates the Coban and Boehm

result for those cases where the internal conduction resistance is considerably

greater than the exterior resistance, which is true in a majority of cases. The

improvement in this version is that the external convection resistance is retained

for those cases when this condition is not met, making this a more universal

expression.

APPENDIX II

DUAL UTILIZATION OPTIMIZATION (DUO) INDICATOR

A measure of whether the temperature profiles of a DCHX are those of a system exhibiting the condition of optimized dual utility can be constructed from a measure of two key characteristics of the profiles - the degree of parallelism and closeness of approach. Parallelism is determined by subtracting the temperature difference at both ends of the DCHX column. If the differentials are equal, the difference will be zero, indicating perfectly parallel inlet and outlet conditions. Conversely, nonparallel profiles retain some value. To convert this measure to one that ranges between 0 and 1 and retains a convention of 0=worst case/1=best case, the absolute value of the differential is divided by the maximum difference possible and subtracted from 1. This results in an indicator for parallelism which becomes a component of the final DUO indicator and is given as follows.

$$\left(1 \ - \ \left|\frac{\Delta T_1 - \Delta T_2}{\Delta T_{max}}\right|\right)$$ II-1

The second component - closeness of approach - is constructed to determine the closeness of approach of the temperature profiles using the commonly known log mean temperature difference (LMTD). The LMTD is

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divided by the maximum possible temperature difference, yielding a value bounded

by 0 and 1. In this manner, the closer the approach is, the smaller the LMTD

derivative becomes, approaching a value of 0 in the limit. The result is then

subtracted from 1 to convert to the convention of 0=non optimum/1=optimum as

follows

$$\left(1 - \frac{LMTD}{\Delta T_{max}}\right)$$ II-2

The two above expressions are multiplied together to form the DUO indicator as

such

$$DUO = \left(1 - \frac{LMTD}{\Delta T_{max}}\right)\left(1 - \left|\frac{\Delta T_1 - \Delta T_2}{\Delta T_{max}}\right|\right)$$ II-3

Like its components, the DUO indicator ranges between 0 and 1 with 1

being the ideal case. It should be noted, though, that the so called *ideal* case -

coincidental profiles - is an impossibility since if there is no temperature

differential, then there is no heat transfer. Rather, the usefulness of the indicator

lies in the location of its peak value as a particular parameter - say, flow rate - is

varied, indicating that the value of the parameter has been found for dual

optimized fluid utility. Further discussion of this indicator and results of its use

are given in Chapters 2 and 3.

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APPENDIX III

DIRECT CONTACT, GAS-FIRED WATER HEATER

Two designs are presented for the adaptation of a spray-column direct

contact heat exchanger for producing hot water in commercial applications from

combustion exhaust. The designs are developed utilizing the numerical simulation

of two and three-phase spray-columns described in this dissertation to demonstrate

the utility of the numerical simulation and to show that such systems are feasible

and substantially less expensive than the classical boiler/shell-and-tube designs.

Overview

Water heating from products of combustion is a frequently applied

industrial process. Principally, this can be accomplished through the use of direct-

contact heat exchangers (DCHXs), the general advantages being DCHXs are (a) a

more efficient, (b) exhibit almost no fouling, and (c) have lower capital costs.

Employing the developed one-dimensional model results in the creation of

of two separate system designs - an *on-demand (OD)* and *thermal reservoir (TR)*.

Simulation analysis of the OD design resulted in a system that permits an *on-*

demand draw of water heated from a tap condition of 22°C to 49°C (72°F to

120°F). The design is made on a water flow rate per unit area of column cross

section and can be sized to meet a particular need. The second system, the

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thermal reservoir (TR), is one that requires the spray-column to double as a thermal storage tank for a quantity of water heated beyond the required use temperature and then mixed with tap condition water in the proper ratio. This design is especially suited for situations where demand flow rate is high but not necessarily continuous and the system can run during off hours or overnight generating the hot reserve supply.

In both cases, the use of a DCHX shows to be highly efficient, having an effectiveness (ϵ) of 1.0. The only limitation is that the water must come in direct contact with combustion exhaust rendering it non-potable and must, therefore, be limited to such as linen cleaning, leather tanning, or industrial applications.

On-Demand Design

The *OD* design is desirable due to the flexible for reasons stated. The design allows for a one pass through on an as-needed basis only and is useful for moderate temperature and flow rate applications. It is the simplest and most true to the counter-flow spray-column DCHX concept. Tap water enters at the top of a spray-column and is heated by a rising flow of hot combustion gases. The exiting water is heated to the desired temperature during the single pass through the spray-column. Such a design is achievable for a variety of output temperatures and flow rates. Several concerns arise in specifying a design for an on-demand system. First, an adequate temperature rise must occur in one pass through. Second, this rise must occur for a reasonable flow rate of water. Natural gas,

which is primarily methane, when combusted with air in the proper ratio, can produce an exhaust gas at 1500°C. The combustion products retain the high percentage of nitrogen from the air therefore exhibiting nearly the same properties as air. Bringing the hot gas in contact with water results in a highly effective transfer leading to two possible outcomes. Either a small flow of water can experience a large increase in temperature or a large flow of water can undergo a small or moderate change in temperature or some combination of the two in accordance with the respective mass rate and thermal capacitance of the fluids. A optimal balance is, of course, the desired goal.

Achieving a usable temperature rise with a substantial flow requires a high combustion gas mass flow which can lead to flooding; the condition where the spray-column ceases to support the counterflow of fluids. At an operating pressure of one atmosphere, simulations show that flooding is likely when the dispersed-to-continuous-mass-flow-rate ratio approaches .15 for the combustion gas temperature stated. This is due to the large difference in fluid densities.

The exact ratio at which flooding occurs is influenced by the initial dispersed gas bubble diameter. The smaller the bubble size, the more efficient the heat transfer is. Typically, diameters ranging from 2 mm to 20 mm are desirable. Small bubble sizes mean more bubbles per unit volume and therefore more total bubble surface area in contact with the continuous fluid for heat transfer. However, total bubble drag also becomes high which leads to flooding in the column. It is necessary to introduce the combustion gas bubble at a size that

precludes flooding but yet is within the accepted limits of the spherical bubble assumption. A design inlet bubble diameter of 16 mm is used.

Table 1 lists the parameters for an *OD* design for a spray-column DCHX operating at a nominal pressure of one atmosphere. These parameters are listed on a per square meter of column cross sectional area. To increase or decrease the output flow requirements, one adjusts the DCHX radius while holding all other parameters constant. The mass flow rate of 0.075 kg/sec of water equates to 272 liters/hr or 72 gal/hr. The system is capable of 9400 watts of transfer when operating at atmospheric pressure which will raise the flow of water from 22°C to 49°C (72°F to 120°F), a rise of 27°C (48°F). The effectiveness of this system in extracting heat from combustion gas is 1.0 based on the inlet conditions of the gas properties. The actual transfer of heat is slightly less due to changes in properties as the gas cools. Further, the heat transfer to the water differs from the heat transfer from gas due to the small amount of heat lost in the mass transfer effects (evaporation of water to the gas bubbles).

Figures 2 through 4 depict profiles of key fluid parameters near the bottom of the column. As mentioned, for the specified dispersed inlet bubble radius, nearly all heat transfer occurs in the first few centimeters of the column just as the combustion gas enters. If the inlet bubble size is allowed to increase the transfer stretches out further along the column height. Figure 5 depicts the trend of control volume transfer for a range of larger bubble sizes. The limitations associated with large bubble diameters (i.e. not retaining a spherical shape and/or

Table III-1 Parameter Specification (Per Unit Cross Section) for On-Demand Spray-Column DCHX Water Heater.

Parameter	Value
Dispersed Fluid	Methane/Air Combust. Products
Flow Rate	.005 kg/sec
Inlet Temp	1500°C
Bubble Dia.	1.6 cm
Continuous Fluid	Water
Flow Rate	.075 kg/sec
Inlet Temp	22°C
DCHX Radius	.564 m
DCHX Length	1.0 m
Operating Press.	101.325 kPa
Actual Heat Transfer Rate to Water	8500 watts
Max Transfer Rate	9400 watts
$\epsilon_{(based\ on\ inlet\ cond.)}$	≈ 1.0
Water Outlet Temperature	49°C
LMTD	87.6°C
Volumetric Heat Transfer Coeff.	96.9 W/m³ °C

possible agglomeration and/or breakup are acknowledged and trends are shown for comparative purposes.

A second and perhaps more preferable method exists for increasing the flow rate and/or temperature rise - that is by increasing the operating pressure. Increasing the pressure increases the density of the inlet exhaust gas which reduces the bubble volume and surface area. This eases flooding tendencies thereby allowing higher combustion gas flow rates which in turn introduces more heat to the system. There is relatively little effect on effectiveness, thus, duty increases proportionally with the pressure.
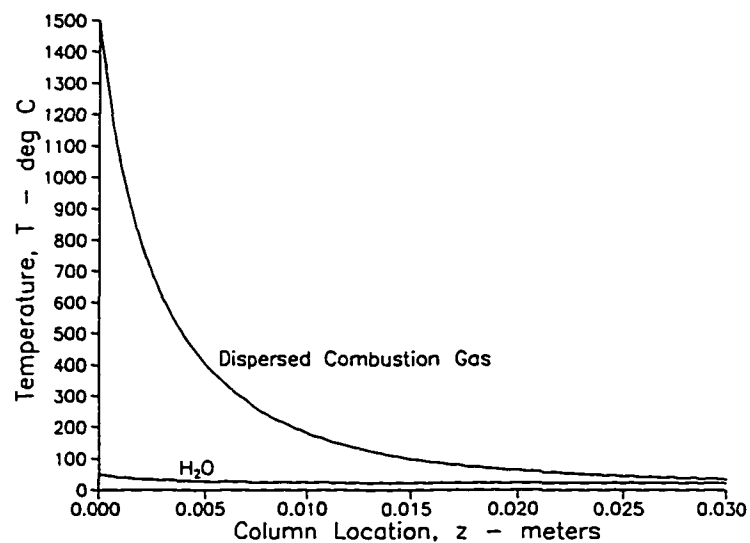
Figure III-1 Temperature Profiles for Bottom Portion of the *On-Demand* System Described in Table III-1.
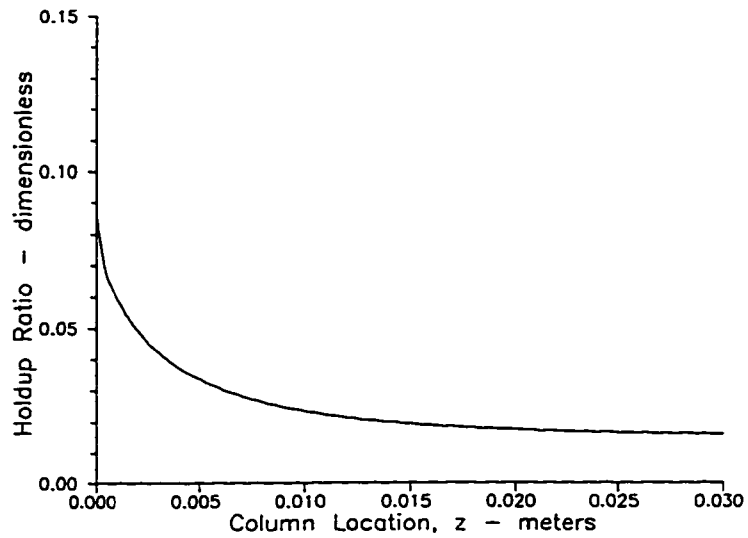
Figure III-2 Holdup Ratio for Bottom Portion of the *OD* System Described in Table III-1.
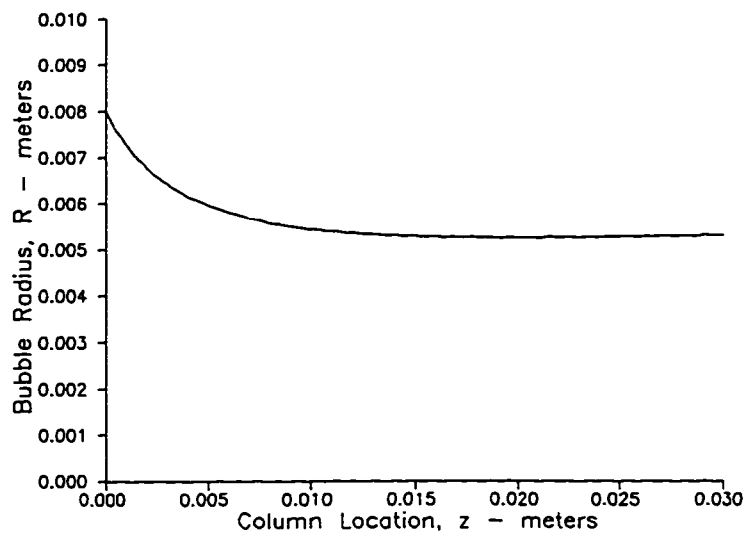
Figure III-3 Dispersed Fluid Bubble Radius for Botto m Portion of the *OD* System Described in Table III-1.
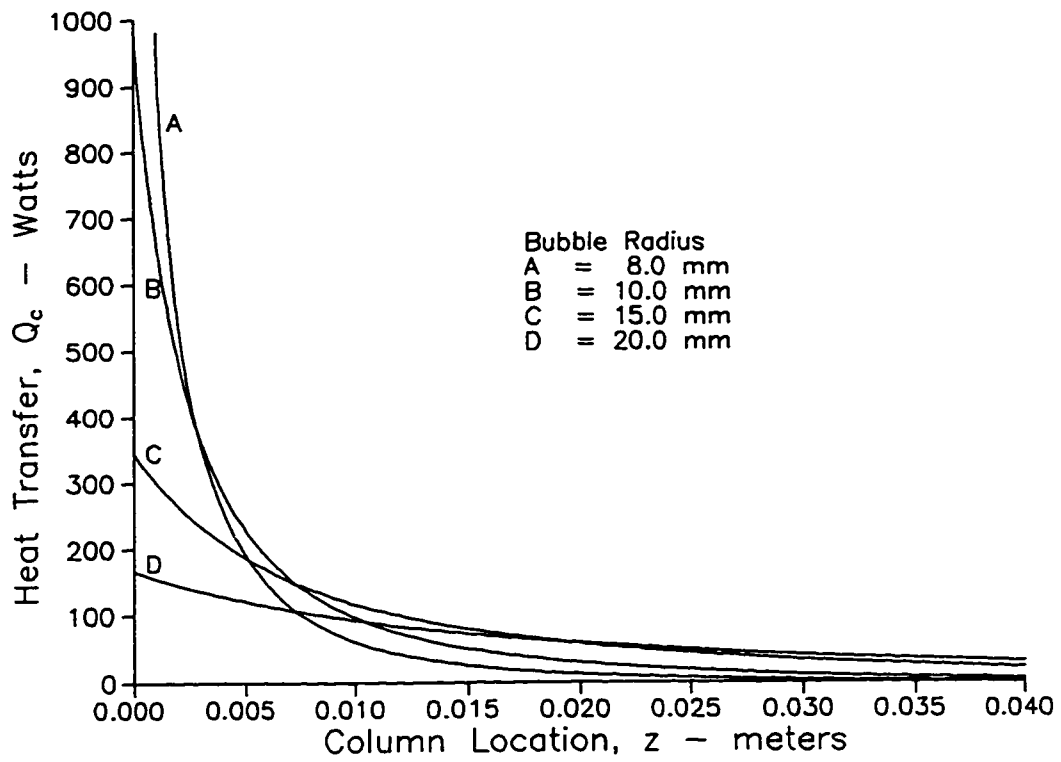
Figure III-4 Control Volume Heat Transfer Profile for *OD* System Described in Table III-1.

Thermal Reservoir Design

Consider an application that requires hot water flow rates of 2.0 kg/sec

($\approx$1900 gal/hr). If the OD design spray-column is sized for this flow, the column

flow area would have to be 27 m^2 equating to a diameter of 2.9 m. For such a

case, an OD system may not be practical since the physical size may not be easily

accommodated. An alternative approach is possible with a system that

continuously recirculates water through a spray-column which doubles as a *thermal*

reservoir. This allows a small system to transfer heat continuously, overshooting

the design temperature in favor of overheating the water. The overheated supply

is mixed with cooler tap water in the proper ratio to supply the higher desired flow

rate at the required temperature. A necessary condition for the TR design is that

the demand is not continuous. The off-demand time is used to build the thermal

reservoir up to the higher temperature for use during a limited period of draw.

The size of a TR system can still be large depending on the amount of water

stored but is considerably smaller than a proportionally sized OD system. The

large size results in very small water flow velocities inside the column - usually on

the order of a few millimeters per second - making this

design similar to the familiar well-stirred reactor with a small flow of the bulk

fluid. The reservoir design generally is selected for continuous heating to higher

temperatures to meet high demand periods of shorter duration.

Table III-2 Parameter Specification for Thermal Reservoir Spray-Column DCHX Water Heater.

Parameter	Value
Dispersed Fluid	Methane/Air Combust. Products
Flow Rate	.045 kg/sec
Inlet Temp	1500°C
Bubble Dia.	3.0 cm
Continuous Fluid	Water
Flow Rate	1.6 kg/sec
Inlet Temp	22°C[t] - 84°C[‡]
DCHX Radius	1.1 m
DCHX Length	5.5 m
Operating Press.	101.325 kPa
Actual Heat Transfer Rate to Water	77,000[t] - 67,500[‡] watts
Max Transfer Rate Possible	84,900[t] - 81300[‡] watts
$\epsilon_{\text{(based on inlet cond.)}}$	≈1.0
Water Temp Rise per pass	12°C[t] - 10°C[‡]
LMTD	94.2°C[t] - 117.3°C[‡]
Volumetric Heat Transfer Coefficient	39.2 W/m³ °C[t] - 27.5 W/m³ °C[‡]
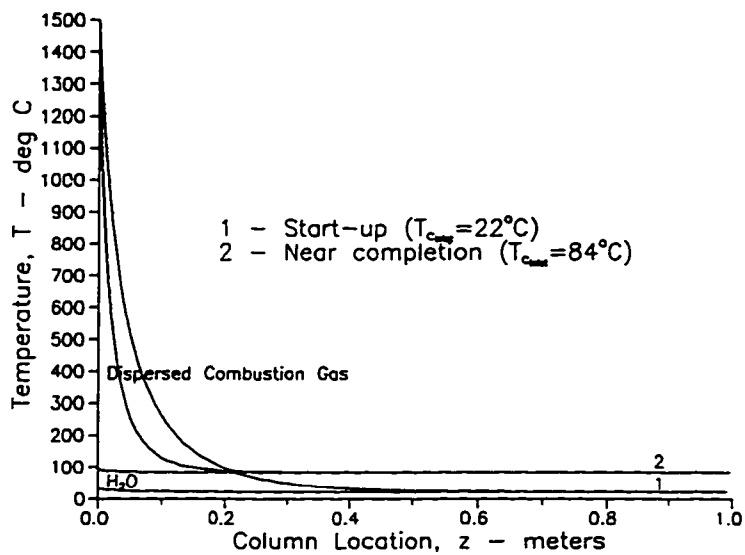
Figure III-5 Temperature Profiles for *Thermal Reservoir* System Described in Table III-2. 1-System Start-Up, 2-Near Completion.
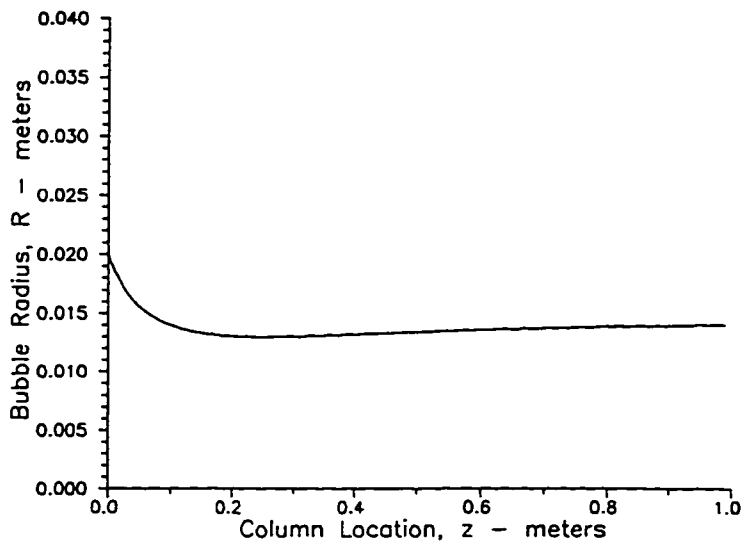
Figure III-6 Typical Profile of Dispersed Bubble Radius for *TR* System Described in Table III-2.
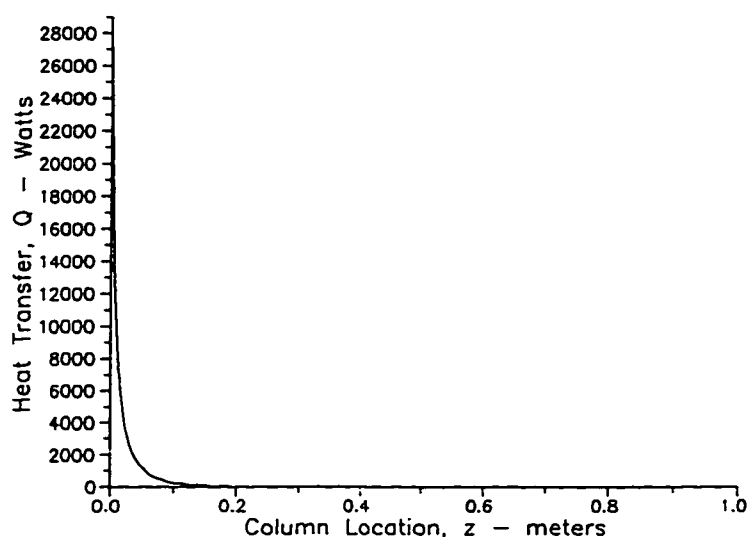
Figure III-7 Control Volume Heat Transfer for *TR* System Described in Table III-2. (Start-up conditions.)

Table 2 lists the parameters of a spray-column system that meets one particular case study in which a user had a requirement for 57000 liters of hot water per day but operated only one 8 hour shift. This system recirculates and heats 21000 liters (5500 gals) of water to 95°C (203°F) which when mixed with 36000 liters (9500 gals) of tap water at 22°C (72°F) will produce 57000 liters (15000 gals) of water at 49°C (120°F). The system operates at a duty of 77,000.

As in the *OD* design, combustion gas is introduced at 1500°C. Water passing through the spray column at the specified parameters will gain an average of 11°C per pass. Exit water is reintroduced at the top of the spray column where is mixes into the bulk flow. Eventually (approximately one day), the total bulk temperature will reach an elevated temperature of 95°C. The 11°C gain holds nearly constant with minimal loss of effectiveness as the mixed temperature entry

water rises to 95°C. This is due to the high temperature of the inlet gas. The max ideal transfer to water starting at 22°C is nearly equal to the ideal transfer for water starting at 84°C since there is less than a 5% difference in the maximum gas/water temperature differential. The ideal transfer holds between 84,900 - 81,300 watts (start - near completion). The effectiveness of extracting heat from the dispersed fluid is again constant at approximately 1.0 with (as stated earlier) the effectiveness of heat transfer into the water being slightly less due to property changes and mass transfer.

Figures 6, 7, and 8 depict typical parametric profiles for the TR system. The inlet bubble diameter given in Table 2 is listed at 3.0 cm. It is acknowledged that some assumptions may break down for this large of a bubble and these effects are accounted for. Figure 7 shows the reduction in the bubble size as it rises and cools to a higher density. Flooding potential only occurs near the dispersed gas inlet and then ceases to be a risk as the bubble shrinks. As in the first design, Figure 8 indicates that a bulk of the heat transfer occurs within the first few percent of length.

System Costs

A cost analysis for the TR design given has been done and compared to a comparably sized boiler/shell and tube system. Spray-column direct contact heat exchangers have inherently lower costs due primarily to less complexity of the systems and the elimination of a substantial amount of material (i.e. numerous tubes) from the exchanger portion. Estimated cost of a TR system is

approximately one fifth of a conventional boiler/shell and tube system.

The total cost of a *TR* system is approximately $6000 (1993 U.S. dollars).

The cost of a comparable conventional system consisting of a boiler, shell and tube

heat exchanger, 3750 liter (1000 gal.) storage vessel, and associated components is

estimated at $33,600 (1993 U.S. dollars) indicating that the cost of the DCHX is

less than 20% that of the conventional system.

APPENDIX IV

CURVE FIT FLUID PROPERTY EXPRESSIONS

Curve fits of fluid property data were constructed for use in the one-

dimensional code. Fluid properties come from a number of sources including

Coban (1986) and references such as Vargaftik (1975) and the *1989 ASHRAE*

Fundamentals Handbook in the case of naturally occurring or common gases and

liquids and promotional pamphlets and brochures for some of the commercially

produced heat transfer fluids. This appendix comprises is a compilation of

expressions used.

(Unless otherwise noted, units are $T(^{\circ}C)$, $c_p(J/kg\text{-}K)$, $\rho(kg/m^3)$, $k(W/m\text{-}k)$, $\mu(Pa\text{-}s)$,

and results are for standard pressure of 101.325 kPa.)

Therminol® 44 *liquid*
TH44

    For -45 < T < 260
    c_p = 2.47558T + 1895.91
    ρ = 940.03 - 0.75776T - 1.2075x10$^{-4}T^2$
    k = 1.4566x10^{-1} - 1.2663x10^{-4}T - 1.5176x10$^{-7}T^2$

    For -45 < T < 10
    μ = .0168827exp(-.0876271T)

    For 10 < T < 260
    μ = .014207 - 5.84755x10^{-4}T + 1.1979x10$^{-5}T^2$ - 1.409x10$^{-7}T^3$
        + 9.8367x10$^{-10}T^4$ - 4.01099x10$^{-12}T^5$ + 8.80257x10$^{-15}T^6$ - 8.0192x10$^{-18}T^7$

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Therminol® 55 - *liquid*
TH55

For 0 < T < 343
c_p = 3.38436T + 1862.95
ρ = 895.12 - 0.66735T - 6.1756x10$^{-6}T^2$
k = .130426 - 8.3889x10^{-5}T - 1.17235x10$^{-7}T^2$

For 0 < T < 38
μ = .301559exp(-.0713115T)

For 38 < T < 343
μ = .104613 - 3.9908x10^{-3}T + 7.0359x10$^{-5}T^2$ - 7.1588x10$^{-7}T^3$ + 4.5138x10$^{-9}T^4$
    - 1.7912x10$^{-11}T^5$ + 4.3535x10$^{-14}T^6$ - 5.9175x10$^{-17}T^7$ + 3.444x10$^{-20}T^8$

Therminol® 60 - *liquid*
TH60

For -50 < T < 343
c_p = 1517.5 + 3.7058T
ρ = 1007.9 - 0.64663T - 6.8946x10$^{-5}T^2$
k = .13363 - 7.6511x10^{-5}T - 3.6863x10$^{-9}T^2$

For -50 < T < 10
μ = .0233656exp(-.0841699T)

For 10 < T < 343
μ = .019873 - 8.1667x10^{-4}T + 1.7149x10$^{-5}T^2$ - 2.0926x10$^{-7}T^3$ + 1.554x10$^{-9}T^4$
    - 7.1014x10$^{-12}T^5$ + 1.9461x10$^{-14}T^6$ - 2.9291x10$^{-17}T^7$ + 1.8593x10$^{-20}T^8$

Therminol® 66 - *liquid*
TH66

For -18 < T < 371
c_p = 1514.7 + 3.5326T
ρ = 1020.3 - 0.67361T - 2.7852x10$^{-5}T^2$
k = .120973 - 5.08537x10^{-5}T - 1.06489x10$^{-7}T^2$

For -18 < T < 49
μ = .928583exp(-.0891155T)
ELSE
For 49 < T < 371
μ = 14.3448$T^{-1.79827}$

Therminol® 88 - *liquid*
TH88

For 149 < T < 482.

c_p = 2.1984T + 1627.2

ρ = -1.2077x10$^{-4}T^2$ - 0.7389T + 1121.2

k = .139621 - 7.9469x10^{-5}T - 2.8337x10$^{-9}T^2$

μ = 3.6914$T^{-2.01174}$

Therminol® VP-1 - *liquid*
MTHVP1

For 15 < T < 404

c_p = 1502.4 + 2.7206T

ρ = 1071.2 - 0.62931T - 7.8203x10$^{-2}T^2$

k = .143285 - 1.53527x10^{-4}T + 2.03924x10$^{-8}T^2$

μ = .00792082 - 2.0877x10^{-4}T + 2.9702x10$^{-6}T^2$ - 2.6742x10$^{-8}T^3$
         + 1.5734x10$^{-10}T^4$ - 5.9706x10$^{-13}T^5$ + 1.3963x10$^{-15}T^6$
         - 1.8196x10$^{-18}T^7$ + 1.0071x10$^{-21}T^8$

Dowtherm® SR-1 - *liquid*
DTSR1

For 0 < T < 125

c_p = 3204.1 + 3.8701T

ρ = 1082.5 - 0.33961T - 2.4148x10$^{-3}T^2$

k = .363 + 9.09344x10^{-4}T - 3.81547x10$^{-6}T^2$

μ = .00733697 - 1.23288x10^{-4}T + 5.53221x10$^{-7}T^2$

Dowtherm® 4000 - *liquid*
DT4000

For 4 < T < 177

c_p = 3169.2 + 3.9563T

ρ = 1096.7 - 0.491T - 1.5049x10$^{-3}T^2$

k = .362926 + 9.2063x10^{-4}T - 3.91495x10$^{-6}T^2$

μ = .00746199 - 1.53974x10^{-4}T + 1.4021x10$^{-6}T^2$ - 2.825x10$^{-9}T^3$

Dowtherm® 4000 (30% Glycol) - *liquid*
DT4030

For 4 < T < 176

c_p = 3741.2 + 1.5305T

ρ = 1061.6 - .346849T - .00193194T^2

k = .437696 + 1.24698x10^{-3}T - 4.8875x10$^{-6}T^2$

μ = -8.3167x10$^{-4}\ln(T)$ + .00441

Dowtherm® 4000 (40% Glycol)- *liquid*
DT4040

For 4 < T < 176

c_p = 3533.9 + 2.8283T - .00219331T^2

ρ = 1071.6 - .34685T - .00193194T^2

k = .403952 + .001046T - 4.1122x10$^{-6}T^2$

μ = -.00116578ln(T) + .00609

Dowtherm® 4000 (50% Glycol) - *liquid*
DT4050

For 4 < T < 176

c_p = 3321.4 + 3.49T - 1.1506x10$^{-3}T^2$

ρ = 1092.4 - .5401T - .0011855T^2

k = .3719 + 8.4555x10^{-4}T - 3.3368x10$^{-6}T^2$

μ = -.00161257ln(T) + .0083384

Dowtherm® 4000 (60% Glycol) - *liquid*
DT4060

For 4 < T < 176

c_p = 3103.8 + 4.4285T - .0020395T^2

ρ = 1112.9 - .754322T

k = .339419 + 7.60199x10^{-4}T - 2.8656x10$^{-6}T^2$

μ = .0323917$T^{-.866}$

Dowfrost® - *liquid*
DWFRST

For 4 < T < 121

c_p = 3455.9 + 3.8394T

ρ = 1054.1 - 0.43901T - 2.5735x10$^{-3}T^2$

k = .349979 + 7.25542x10^{-4}T - 4.00611x10$^{-6}T^2$

μ = .0152155 - 2.79327x10^{-4}T + 1.30927x10$^{-6}T^2$

Dowfrost® HD - *liquid*
DWFHD

For 4 < T < 177

c_p = 3297.7 + 5.0675T - 4.9202x10$^{-3}T^2$

ρ = 1071.4 - 0.61005T - 9.05x10$^{-4}T^2$

k = .34947 + 8.504x10^{-4}T - 6.3946x10$^{-6}T^2$ + 1.1496x10$^{-7}T^3$

μ = .0155255 - 3.5542x10^{-4}T + 2.765x10$^{-6}T^2$ - 7.0061x10$^{-9}T^3$

Dowfrost® HD (30% Glycol) - *liquid*
DFHD30

For $4 < T < 162$

$c_p = 3894.6 + 1.7059T - 2.2976 \times 10^{-3}T^2$

$\rho = 1052.6 - .587151T - 6.4261 \times 10^{-4}T^2$

$k = .4205 + .0012295T - 5.4564 \times 10^{-6}T^2$

$\mu = \frac{1}{2}(.004767\exp(-.018319T) + .018137T^{-.780412})$

Dowfrost® HD (40% Glycol) - *liquid*
DFHD40

For $4 < T < 162$

$c_p = 3736.9 + 2.3371T - 2.11822 \times 10^{-3}T^2$

$\rho = 1062.3 - .51924T - .00142626T^2$

$k = .38 + 9.759 \times 10^{-4}T - 4.0706 \times 10^{-6}T^2$

$\mu = \frac{1}{2}(.0077474\exp(-.020585T) + .0352158T^{-.880378})$

Dowfrost® HD (50% Glycol) - *liquid*
DFHD50

For $4 < T < 162$

$c_p = 3496.9 + 3.5702T - .0020608T^2$

$\rho = 1073 - .757688T$

$k = .34087 + 8.2641 \times 10^{-4}T - 3.3728 \times 10^{-6}T^2$

$\mu = \frac{1}{2}(.0117985\exp(-.022392T) + .0601634T^{-.952745})$

Dowfrost® HD (60% Glycol) - *liquid*
DFHD60

For $4 < T < 162$

$c_p = 3257 + 4.80134T - 1.9952 \times 10^{-3}T^2$

$\rho = 1072.3 - .519239T - .00142626T^2$

$k = .30883 + 6.3162 \times 10^{-4}T - 2.6656 \times 10^{-6}T^2$

$\mu = \frac{1}{2}(.0194357\exp(-.025182T) + .123987T^{-1.07719})$

Paratherm® NF - *liquid*
PARANF

For $10 < T < 316$

$c_p = 1810.9 + 3.5594T$

$\rho = 729.65 - 0.33504T$

$k = .13431 - 7.0226 \times 10^{-5}T$

$\mu = 4.40572T^{-1.60423}$

Paratherm® HE - *liquid*
PARAHE

For $10 < T < 316$

$c_p = 1876.8 + 4.1316T$

$\rho = 746.1 - 0.63119T$

$k = 0.13455 - 7.4724 \times 10^{-5}T$

$\mu = 795.75T^{-2.70403}$

CALFLO AF - *liquid*
CFAF

For $40 < T < 316$

$c_p = 1714.9 + 3.8688T$

$\rho = 862.89 - 0.63225T + 4.0234 \times 10^{-4}T^2$

$k = .13807 - 5.4571 \times 10^{-5}T + 1.7361 \times 10^{-9}T^2$

$\rho = 39.7783T^{-1.99202}$

CALFLO FG - *liquid*
CFFG

For $40 < T < 288$

$c_p = 1803.8 + 3.3423T$

$\rho = 854.12 - 0.27305T - 7.5461 \times 10^{-4}T^2$

$k = .13913 - 8.5789 \times 10^{-5}T + 9.1377 \times 10^{-8}T^2$

$\mu = 3.62695T^{-1.55491}$

CALFLO HTF - *liquid*
CFHTF

For $40 < T < 316$

$c_p = 1845.8 + 3.2776T$

$\rho = 871.0 - 0.58587T + 2.2249 \times 10^{-4}T^2$

$k = .13907 - 5.4571 \times 10^{-5} + 1.7361 \times 10^{-9}T^2$

$\mu = 50.8759T^{-2.00572}$

Syltherm® 800 - *liquid*
SYLTH8

For $-73 < T < 260$

$c_p = 1574.5 + 1.7067T$

$\rho = 955.89 - 0.81738T - 4.8042 \times 10^{-4}T^2$

$k = .10792 - 6.52567 \times 10^{-5}T + 1.74916 \times 10^{-9}T^2$

For -73 < T < 10
μ = .00220438 - 3.9223x10^{-5}T - 4.6422x10^{-7}T - 2.5722x10$^{-8}T^3$

For 10 < T < 260
μ = .00202134 - 3.07134x10^{-5}T + 2.34941x10$^{-7}T^2$ - 8.7194x10$^{-10}T^3$
   + 1.22576x10$^{-12}T^4$

Thermalane® 550 - liquid
THM550

For 17 < T < 316
c_p = 1989.5 + 3.3681T
ρ = 852.91 - 0.67118T
k = .14486 - 7.4074x10^{-5}T

For -17 < T < 4.5
μ = .184015exp(-.0602736T)

For 4.5 < T < 316
μ = .174439 - 8.1538x10^{-3}T + 1.8709x10$^{-4}T^2$ - 2.5991x10$^{-6}T^3$ + 2.3307x10$^{-8}T^4$
   - 1.37384x10$^{-10}T^5$ + 5.27456x10$^{-13}T^6$ - 1.2669x10$^{-15}T^7$
   + 1.72579x10$^{-18}T^8$ - 1.01648x10$^{-21}T^9$

Thermalane® 600 - liquid
THM600

For -17 < T < 327
c_p = 2094.7 + 3.1495T
ρ = 835.58 - 0.65347T
k = .15629 - 6.196x10^{-5}T

For -17 < T < 4.5
μ = .182273exp(-.0732021T)

For 4.5 < T < 327
μ = .170328 - 8.7649x10^{-3}T + 2.1606x10$^{-4}T^2$ - 3.1393x10$^{-6}T^3$ + 2.8835x10$^{-8}T^4$
   - 1.716x10$^{-10}T^5$ + 6.5874x10$^{-13}T^6$ - 1.5717x10$^{-15}T^7$ + 2.1173x10$^{-18}T^8$
   - 1.2293x10$^{-21}T^9$

Thermalane® 800 - *liquid*
THM800

For -17 < T < 371

c_p = 2184.5 + 3.2144T - 9.6370x10$^{-4}T^2$

ρ = 2184.5 + 3.2144^T - 9.6370x10$^{-4}T^2$

k = .1529 - 1.0318x10^{-4}T - 7.4183x10$^{-9}T^2$

μ = .126335 - 6.0631x10^{-3}T + 1.1617x10$^{-4}T^2$ - 1.134x10$^{-6}T^3$ + 6.1506x10$^{-9}T^4$
   - 1.8752x10$^{-11}T^5$ + 3.00614x10$^{-14}T^6$ - 1.971x10$^{-17}T^7$

Thermex® - *liquid*
THRMX

(Temperature limits unknown)

c_p = 2.83089T + 1528.32

ρ = -.938571T + 1089.29

k = -1.3333x10^{-4}T + .14319

μ = .27911$T^{-1.23818}$

Air - *gas*
AIR

For -173 < T < 2726

c_p = 1005.28 + 5.3251x10^{-3}T + 6.337x10$^{-4}T^2$ - 8.1579x10$^{-7}T^3$
   + 4.9426x10$^{-10}T^4$ - 1.5492x10$^{-13}T^5$ + 2.3265x10$^{-17}T^6$

k = 0.0254297 + 8.3037x10^{-5}T - 9.6375x10$^{-8}T^2$ + 1.286x10$^{-10}T^3$
   - 7.3051x10$^{-14}T^4$ + 1.5801x10$^{-17}T^5$

μ = 1.71833x10^{-5} + 5.0923x10^{-8}T - 3.8357x10$^{-11}T^2$ + 2.8467x10$^{-14}T^3$
   - 9.9701x10$^{-18}T^4$ + 1.3181x10$^{-21}T^5$

For -173 < T < 26

ρ = 1.26941 - 4.886x10^{-3}T + 2.5977x10$^{-5}T^2$ + 1.8185x10$^{-7}T^3$ + 1.7867x10$^{-9}T^4$

For 26 < T < 2225

ρ = 1.26214 - 4.1154x10^{-3}T + 1.011x10$^{-5}T^2$ - 1.6588x10$^{-8}T^3$ + 1.7341x10$^{-11}T^4$
   - 1.1284x10$^{-14}T^5$ + 4.3989x10$^{-18}T^6$ - 9.3648x10$^{-22}T^7$ + 8.3467x10$^{-26}T^8$

For 2225 < T < 2726

ρ = 0.350535 - 1.313x10^{-4}T + 1.6274x10$^{-8}T^2$

Carbon Dioxide [CO_2] - *gas*
CO2

For -53 < T < 1526

c_p = 827.967 + 0.99954T - 8.4763x10$^{-4}T^2$ + 3.8487x10$^{-7}T^3$ - 7.1375x10$^{-11}T^4$

ρ = 1.9713 - 5.8952x10^{-3}T + 9.8244x10$^{-6}T^2$ - 7.5549x10$^{-9}T^3$ + 2.0916x10$^{-12}T^4$

k = 1.4448x10^{-2} + 8.3527x10^{-5}T - 1.3133x10$^{-8}T^2$

μ = 1.4589x10^{-5} + 3.8088x10^{-8}T - 6.2015x10$^{-12}T^2$

Hydrogen [H_2] - *gas*
H2

For -173 < T < 1726

c_p = 14183.4 + 5.5081T - .037213T^2 + 1.2355x10$^{-4}T^3$ - 2.2182x10$^{-7}T^4$
  + 2.3445x10$^{-10}T^5$ - 1.4451x10$^{-13}T^6$ + 4.77946x10$^{-17}T^7$ - 6.51397x10$^{-21}T^8$

ρ = .087964 - 3.0046x10^{-4}T + 1.247x10$^{-6}T^2$ - 6.5073x10$^{-9}T^3$ + 2.4773x10$^{-11}T^4$
  - 5.7169x10$^{-14}T^5$ + 8.0088x10$^{-17}T^6$ - 6.8746x10$^{-20}T^7$ + 3.5342x10$^{-23}T^8$
  - 9.9886x10$^{-27}T^9$ + 1.19331x10$^{-30}T^{10}$

k = .167244 + 4.9794x10^{-4}T - 3.0927x10$^{-7}T^2$ + 2.6862x10$^{-10}T^3$
  - 6.87395x10$^{-14}T^4$

μ = 8.26065x10^{-6} + 2.0427x10^{-8}T - 6.8867x10$^{-12}T^2$ + 1.7348x10$^{-15}T^3$

Nitrogen [N_2] - *gas*
N2

For -173 < T < 1026

c_p = 1039.9 - .033984T + 6.0155x10$^{-4}T^2$ - 5.3704x10$^{-7}T^3$ + 1.4479x10$^{-10}T^4$

ρ = 1.2826 - 4.5158x10^{-3}T + 1.0512x10$^{-5}T^2$ - 5.0297x10$^{-8}T^3$ + 4.2596x10$^{-10}T^4$
  - 1.8193x10$^{-12}T^5$ + 3.9745x10$^{-15}T^6$ - 4.6671x10$^{-18}T^7$ + 2.8145x10$^{-21}T^8$
  - 6.8517x10$^{-25}T^9$

k = .023643 + 7.4477x10^{-5}T - 3.9978x10$^{-8}T^2$ + 2.1437x10$^{-11}T^3$

μ = 1.6277x10^{-5} + 4.7868x10^{-8}T - 2.9288x10$^{-11}T^2$ + 1.1255x10$^{-14}T^3$

Oxygen [O_2] - *gas*
O2

For -173 < T < 1026

c_p = 913.86 + .090997T + .0013194T^2 - 3.1674x10$^{-6}T^3$ + 3.00295x10$^{-9}T^4$
  - 1.03672x10$^{-12}T^5$

ρ = 1.4662 - 5.1602x10^{-3}T + 1.1947x10$^{-5}T^2$ - 5.7867x10$^{-8}T^3$ + 4.9429x10$^{-10}T^4$
  - 2.114x10$^{-12}T^5$ + 4.6193x10$^{-15}T^6$ - 5.4242x10$^{-18}T^7$ + 3.2709x10$^{-21}T^8$
  - 7.9618x10$^{-25}T^9$

k = .0235842 + 7.58894x10^{-5}T - 1.43399x10$^{-8}T^2$

μ = 1.90145x10^{-5} + 5.8246x10^{-8}T - 4.16376x10$^{-11}T^2$ + 2.14079x10$^{-14}T^3$

Ammonia [NH$_3$] - *gas*
NH3

For 26 < T < 306

c_p = 2134.76 + .538392T + .0063678T^2 - 9.9898x10$^{-6}T^3$

ρ = .73673 - .00209815T + 2.8379x10$^{-6}T^2$

μ = 9.1404x10^{-6} + 3.80243x10^{-8}T - 9.0094x10$^{-12}T^2$

k = .022197 :- 8.65576x10^{-5}T + 3.232x10$^{-7}T^2$ - 5.4597x10$^{-10}T^3$

MS-20 Oil - *liquid*
MS20

(Temperature limits unknown)

c_p = 3.09412T + 1980.44

ρ = -0.56681T + 903.679

k = 8.57848x10$^{-8}T^2$ - 1.19191x10^{-4}T + .136087

μ = 4331.33$T^{-2.69759}$

Transformer Oil (Standard 982-68) - *liquid*
TRAN

(Temperature limits unknown)

c_p = -1.5597x10$^{-9}T^6$ + 3.6213x10$^{-7}T^5$ - 1.7345x10$^{-5}T^4$ - 1.4121x10$^{-3}T^3$
    + .12049T^2 + 3.04729T + 1616.47

ρ = -.62105T + 891.364

k = -8.19549x10^{-5}T + .112297

μ = .0406485exp(-.032348T)

TM-1 (VTU-M3-11-62) - *liquid*
TM1

For -50 < T < 100

c_p = 1.20508T + 1618.48

ρ = -0.63744T + 902.499

k = -9.53055x10^{-5}T + .120687

μ = .382997$T^{-1.08805}$

VM-4 Oil (Standard 7903-56) - *liquid*
VM4

For -30 < T < 100

c_p = -2.3592x10$^{-9}T^6$ + 5.4339x10$^{-7}T^5$ - 3.7219x10$^{-5}T^4$ + 3.022x10$^{-4}T^3$
    + 0.04831T^2 +.23315T + 1457.74

ρ = -0.5915T + 915.492

k = -8.94004x10^{-5}T + .129112

μ = 61.3841$T^{-1.85956}$

KhF22 Oil (Standard 5546-66) - *liquid*
KHF22

(Temperature limits unknown)

$c_p = -1.58271 \times 10^{-6}T^4 + 6.52884 \times 10^{-5}T^3 + 0.012453T^2 + .241957T + 1638.96$

$\rho = -0.72984T + 1009.52$

$k = -1.48464 \times 10^{-4}T + .157694$

$\mu = 2.57617T^{-1.30322}$

Engine Oil (Unused) - *liquid*
ENG

For $0 < T < 156$

$c_p = 1798.42 + 4.06543T + .001455T^2$

$\rho = 899.55 - .5926T$

$k = .147 - 7.18122 \times 10^{-5}T - 7.0708 \times 10^{-7}T^2 + 3.6242 \times 10^{-9}T^3$

$\mu = 3.8022 - .31428T + .013304T^2 - 3.5893T^3 + 6.4967 \times 10^{-6}T^4$
$\quad - 7.9143 \times 10^{-8}T^5 + 6.3585 \times 10^{-10}T^6 - 3.2142 \times 10^{-12}T^7 + 9.2318 \times 10^{-15}T^8$
$\qquad - 1.146 \times 10^{-17}T^9$

Ethylene Glycol [$C_2H_4(OH)_2$] - *liquid*
ETHYLG

For $0 < T < 100$

$c_p = 2293.78 + 4.4801T$

$\rho = 1129.76 - .23264T - .026345T^2 + 4.5083 \times 10^{-4}T^3 - 2.3342 \times 10^{-6}T^4$

$k = .24194 + 3.205 \times 10^{-4}T + 2.4239 \times 10^{-6}T^2 - 4.34 \times 10^{-9}T^3 - 1.1914 \times 10^{-9}T^4$
$\quad - 8.8208 \times 10^{-12}T^5$

$\mu = .06442 - .0041299T + 1.4896 \times 10^{-4}T^2 - 3.2665 \times 10^{-6}T^3 + 4.1721 \times 10^{-8}T^4$
$\quad - 2.8171 \times 10^{-10}T^5 + 7.4264 \times 10^{-13}T^6$

Glycerin [$C_3H_5(OH)_3$] - *liquid*
GLYCRN

For $0 < T < 46$

$c_p = 2260.92 + 5.8326T + .01288T^2$

$\rho = 1275.52 - .5666T - 7.2682 \times 10^{-4}T^2$

$k = .282065 + 3.4417 \times 10^{-4}T - 1.0215 \times 10^{-5}T^2 + 1.0936 \times 10^{-7}T^3$

$\mu = 10.457 - .98243T + .03866T^2 - 7.1174 \times 10^{-4}T^3 + 5.0052 \times 10^{-6}T^4$

Mercury (Hg) - *liquid*

HG

For $0 < T < 326$

$c_p = 1403.48 - .3996T + 7.7106 \times 10^{-4} T^2$

$\rho = 13592.9 - 2.4009T$

$k = 8.1777 + .013656T - 6.49055 \times 10^{-6} T^2$

$\mu = .0016815 - 6.15448 \times 10^{-6} T + 1.96029 \times 10^{-8} T^2 - 2.4526 \times 10^{-11} T^3$

n-Pentane - *liquid*

PENT

For $0 < T < 200$

$c_p = $ *Determined by subroutine (Riemer, 1976b)*

$\rho = $ *Determined by subroutine (Riemer, 1976b)*

$k = .120500001 - 2.19166518 \times 10^{-4} T - 1.4583602 \times 10^{-6} T^2 + 4.1667695 \times 10^{-8} T^3$
$\quad - 4.16677821 \times 10^{-10} T^4$

$\mu = 2.8306484 \times 10^{-4} - 4.7037877 \times 10^{-6} T + 3.9457157 \times 10^{-7} T^2$
$\quad - 2.20408288 \times 10^{-8} T^3 + 5.8042066 \times 10^{-10} T^4 - 7.813455978 \times 10^{-12} T^5$
$\quad + 5.23570269 \times 10^{-14} T^6 - 1.38655465 \times 10^{-16} T^7$

n-Pentane - *vapor*

PENT

For $0 < T < 200$

$c_p = $ *Determined by subroutine (Riemer, 1976b)*

$\rho = $ *Determined by subroutine (Riemer, 1976b)*

$k = .0117000943 + .0974954646 \times 10^{-3} T + 1.2506797 \times 10^{-7} T^2$
$\quad - 3.20993285 \times 10^{-10} T^3$

$\mu = 49.3702925 \times 10^{-7} + .938695079 \times 10^{-7} T - .0151413279 \times 10^{-7} T^2$
$\quad + 1.38067486 \times 10^{-11} T^3 - 4.01657705 \times 10^{-14} T^4$

Butane - *liquid*

BUT

(Temperature limits unknown)

$c_p = $ *Determined by subroutine (Riemer, 1976b)*

$\rho = $ *Determined by subroutine (Riemer, 1976b)*

$k = -7.81255 \times 10^{-10} T^4 + 2.60419 \times 10^{-7} T^3 - 3.21878 \times 10^{-5} T^2$
$\quad + .00149585T + .0749995$

$\mu = -8.41033 \times 10^{-14} T^5 + 3.28754 \times 10^{-11} T^4 - 5.00885 \times 10^{-9} T^3$
$\quad + 3.7359 \times 10^{-7} T^2 - 1.47048T + .000376398$

Butane - *vapor*
BUT

(Temperature limits unknown)

c_p = *Determined by subroutine (Riemer, 1976b)*

ρ = *Determined by subroutine (Riemer, 1976b)*

$k = -4.3704 \times 10^{-11} T^3 + 1.01398 \times 10^{-7} T^2 + .000108024T + .01310114$

$\mu = -7.04548 \times 10^{-18} T^5 + 6.15458 \times 10^{-15} T^4 - 2.03319 \times 10^{-12} T^3$
$\quad + 2.99428 \times 10^{-10} T^2 + 5.54933 \times 10^{-9} T + 7.46943 \times 10^{-6} T$

Isopentane - *liquid*
ISOP

(Temperature limits unknown)

c_p = *Determined by subroutine (Riemer, 1976b)*

ρ = *Determined by subroutine (Riemer, 1976b)*

$k = -8.88886 \times 10^{-8} T^3 + 4.63094 \times 10^{-6} T^2 - .0002988497 + .11906$

$\mu = -1.66661 \times 10^{-10} T^3 + 1.99997 \times 10^{-8} T^2 - 2.78333 \times 10^{-6} T + .000272$

Isopentane - *vapor*
ISOP

(Temperature limits unknown)

c_p = *Determined by subroutine (Riemer, 1976b)*

ρ = *Determined by subroutine (Riemer, 1976b)*

$k = .014023604 + .1208272 \times 10^{-3} T + 1.08600139 \times 10^{-7} T^2 - 1.9940388 \times 10^{-8} T^3$
$\quad + 4.904895 \times 10^{-10} T^4 - 4.92943376 \times 10^{-12} T^5 + 2.2305489 \times 10^{-14} T^6$
$\quad - 3.7421512 \times 10^{-17} T^7$

$\mu = -2.09459 \times 10^{-12} T^2 + 2.224021 \times 10^{-8} T + 6.38969 \times 10^{-6}$

Isobutane - *liquid*
ISOB

(Temperature limits unknown)

c_p = *Determined by subroutine (Riemer, 1976b)*

ρ = *Determined by subroutine (Riemer, 1976b)*

$k = .10545730 - .5897775 \times 10^{-3} T + .27657500 \times 10^{-5} T^2$

$\mu = 1.55136 \times 10^{-10} T^3 - 6.16567 \times 10^{-9} T^2 - 2.09543 \times 10^{-6} T + .000214$

Isobutane - *vapor*
ISOB

> *(Temperature limits unknown)*
> c_p = *Determined by subroutine (Riemer, 1976b)*
> ρ = *Determined by subroutine (Riemer, 1976b)*
> k = .013813870 + .1088360x10^{-3}T + .3069733333x10$^{-06}T^2$
>   -.334880x10$^{-08}T^3$ + .1116266667x10$^{-10}T^4$
> μ = -4.35675x10$^{-14}T^4$ + 1.22251x10$^{-11}T^3$ - 1.22875x10$^{-9}T^2$
>   + 7.04506x10^{-8}T + 6.17173x10^{-6}

Heptane - *liquid*
HEP

> For -90 < T < 20
> c_p = *Determined by subroutine (Riemer, 1976b)*
> ρ = *Determined by subroutine (Riemer, 1976b)*
> k = .13420 - 2.7167x10^{-4}T + 4.8701x10$^{-8}T^2$

> For -90 < T < 20
> μ = 5.2757x10^{-4} - 7.8221x10^{-6}T + 5.2534x10$^{-8}T^2$ + 1.9301x10$^{-9}T^3$
>   + 5.5358x10$^{-11}T^4$

Heptane - *vapor*
HEP

> For -90 < T < 400
> c_p = *Determined by subroutine (Riemer, 1976b)*
> ρ = *Determined by subroutine (Riemer, 1976b)*
> k = 8.8553x10^{-3} + 9.2249x10^{-5}T + 7.1772x10$^{-8}T^2$
> μ = 5.3255x10^{-6} + 2.0043x10^{-8}T + 2.6577x10$^{-13}T^2$

Methane - *liquid*
METH

> For -173 < T < 83
> c_p = *Determined by subroutine (Riemer, 1976b)*
> ρ = *Determined by subroutine (Riemer, 1976b)*
> k = .23242 + 4.6197x10^{-3}T + 4.2448x10$^{-5}T^2$ + 9.6463x10$^{-8}T^3$
> μ = 6.7496x10^{-5} + 1.4941x10^{-6}T + 1.1267x10$^{-8}T^2$

Methane - *vapor*
METH

For -173 < T < 83

c_p = Determined by subroutine (Riemer, 1976b)
ρ = Determined by subroutine (Riemer, 1976b)
k = .030875 + $1.3364 \times 10^{-4} T$ + $9.8656 \times 10^{-8} T^2$
μ = 1.025×10^{-5} + $3.2756 \times 10^{-8} T$ - $1.8745 \times 10^{-11} T^2$

Ethylene - *liquid*
ETHYL

For -165 < T < 225

c_p = Determined by subroutine (Riemer, 1976b)
ρ = Determined by subroutine (Riemer, 1976b)
k = 8.1027×10^{-2} - $1.2232 \times 10^{-3} T$ - $1.2078 \times 10^{-6} T^2$
μ = -2.3585×10^{-3} - $6.3783 \times 10^{-5} T$ - $5.527 \times 10^{-7} T^2$ - $1.6643 \times 10^{-9} T^3$

Ethylene - *vapor*
ETHYL

For -165 < T < 225

c_p = Determined by subroutine (Riemer, 1976b)
ρ = Determined by subroutine (Riemer, 1976b)
k = 1.6976×10^{-2} + $1.2134 \times 10^{-4} T$ + $1.2177 \times 10^{-7} T^2$
μ = 9.4809×10^{-6} + $3.2084 \times 10^{-8} T$ - $1.1608 \times 10^{-11} T^2$

Freon® R-11 Refrigerant - *liquid*
F11

For 0 < T < 150

c_p = Determined by subroutine (Riemer, 1976c)
ρ = Determined by subroutine (Riemer, 1976c)
k = 9.5768×10^{-2} - $2.4018 \times 10^{-4} T$ + $4.7302 \times 10^{-8} T^2$
μ = 5.6689×10^{-4} - $6.5163 \times 10^{-6} T$ + $3.436 \times 10^{-8} T^2$ - $7.393 \times 10^{-11} T^3$

Freon® R-11 Refrigerant - *vapor*
F11

For 0 < T < 150

c_p = Determined by subroutine (Riemer, 1976c)
ρ = Determined by subroutine (Riemer, 1976c)
k = 8.1527×10^{-3} + $2.3475 \times 10^{-5} T$ + $1.8628 \times 10^{-7} T^2$
μ = 1.0179×10^{-5} + $3.0692 \times 10^{-8} T$ + $9.3987 \times 10^{-11} T^2$

Freon® R-13 Refrigerant - *liquid*
F13

For $0 < T < 100$

c_p = Determined by subroutine (Riemer, 1976c)
ρ = Determined by subroutine (Riemer, 1976c)
k = $5.3061 \times 10^{-2} - 2.9112 \times 10^{-4} T + 1.7371 \times 10^{-6} T^2$
μ = $1.0132 \times 10^{-4} - 3.6831 \times 10^{-7} T + 2.8835 \times 10^{-8} T^2$

Freon® R-13 Refrigerant - *vapor*
F13

For $0 < T < 100$

c_p = Determined by subroutine (Riemer, 1976c)
ρ = Determined by subroutine (Riemer, 1976c)
k = $1.3605 \times 10^{-2} + 1.5381 \times 10^{-4} T + 7.7252 \times 10^{-7} T^2$
μ = $1.4922 \times 10^{-5} + 1.163 \times 10^{-7} T + 1.2104 \times 10^{-9} T^2 + 8.2369 \times 10^{-12} T^3$

Freon® R-22 Refrigerant - *liquid*
F22

For $-20 < T < 60$

c_p = Determined by subroutine (Riemer, 1976c)
ρ = Determined by subroutine (Riemer, 1976c)
k = $9.6174 \times 10^{-2} - 4.2368 \times 10^{-4} T + 3.4954 \times 10^{-7} T^2$
μ = $2.1019 \times 10^{-4} - 2.2755 \times 10^{-6} T + 1.0823 \times 10^{-8} T^2$

Freon® R-22 Refrigerant - *vapor*
F22

For $-20 < T < 60$

c_p = Determined by subroutine (Riemer, 1976c)
ρ = Determined by subroutine (Riemer, 1976c)
k = $9.5013 \times 10^{-3} + 6.0705 \times 10^{-5} T - 1.8442 \times 10^{-8} T^2$
μ = $1.18 \times 10^{-5} + 4.0 \times 10^{-8} T$

Freon® R-23 Refrigerant - *liquid*
F23

For $-40 < T < 10$

c_p = Determined by subroutine (Riemer, 1976c)
ρ = Determined by subroutine (Riemer, 1976c)
k = $7.4817 \times 10^{-2} - 7.547 \times 10^{-4} T - 1.4837 \times 10^{-6} T^2$
μ = $9.0309 \times 10^{-5} - 1.6701 \times 10^{-6} T + 4.2279 \times 10^{-9} T^2$

Freon® R-23 Refrigerant - *vapor*
F23

For -40 < T < 10

c_p = *Determined by subroutine (Riemer, 1976c)*
ρ = *Determined by subroutine (Riemer, 1976c)*
k = $1.7685 \times 10^{-2} + 2.1117 \times 10^{-4} T + 1.2942 \times 10^{-6} T^2$
μ = $1.5063 \times 10^{-5} + 1.3885 \times 10^{-7} T + 1.657 \times 10^{-9} T^2$

Freon® R-113 Refrigerant - *liquid*
F113

For 0 < T < 170

c_p = *Determined by subroutine (Riemer, 1976c)*
ρ = *Determined by subroutine (Riemer, 1976c)*
k = $8.1947 \times 10^{-2} - 1.7689 \times 10^{-4} T + 1.3415 \times 10^{-8} T^2$
μ = $9.4573 \times 10^{-4} - 1.1889 \times 10^{-5} T + 7.0746 \times 10^{-8} T^2 - 1.6326 \times 10^{-10} T^3$

Freon® R-113 Refrigerant - *vapor*
F113

For 0 < T < 170

c_p = *Determined by subroutine (Riemer, 1976c)*
ρ = *Determined by subroutine (Riemer, 1976c)*
k = $7.7373 \times 10^{-3} + 4.3806 \times 10^{-5} T + 5.8518 \times 10^{-8} T^2$
μ = $8.1603 \times 10^{-6} + 8.025 \times 10^{-8} T - 6.2726 \times 10^{-10} T^2 + 2.3745 \times 10^{-12} T^3$

Freon® R-114 Refrigerant - *liquid*
F114

For -40 < T < 115

c_p = *Determined by subroutine (Riemer, 1976c)*
ρ = *Determined by subroutine (Riemer, 1976c)*
k = $7.0594 \times 10^{-2} - 2.389 \times 10^{-4} T + 4.0843 \times 10^{-9} T^2$
μ = $4.9155 \times 10^{-4} - 6.5554 \times 10^{-6} T + 4.3739 \times 10^{-8} T^2 - 1.2737 \times 10^{-10} T^3$

Freon® R-114 Refrigerant - *vapor*
F114

For -40 < T < 115

c_p = *Determined by subroutine (Riemer, 1976c)*
ρ = *Determined by subroutine (Riemer, 1976c)*
k = $8.1576 \times 10^{-5} T + .00882409$
μ = $1.0578 \times 10^{-5} + 3.2039 \times 10^{-8} T + 1.2712 \times 10^{-10} T^2$

APPENDIX V

ONE-DIMENSIONAL SIMULATION: PROGRAM USAGE

The program consists of the main execution code containing all required

subroutines, one input file, and seven output files. The files are named

dcx.f — FORTRAN code.

dxin.dat — Input file.

dxout.dat — Output file containing summary of DCHX operation.

dxoutd.dat — Output file containing dispersed fluid profile

dxoutd1.dat — Output file (Additional dispersed fluid parameters)

dxoutd2.dat — Output file (Additional dispersed fluid parameters)

dxoutc.dat — Output file containing continuous fluid profile.

dxoutc1.dat — Output file (Additional continuous fluid parameters)

dxoutfh.dat — Output file containing pertinent DCHX fluid characteristics

parameters

The input file is required for execution. Output files are created by the program

and overwritten with each consecutive use. The input file must contain the

parameters explained in the paragraphs below. All parameters are entered and

reported in S.I. units.

132

Input File - [dxin.dat]

The input file is where the user specifies system size, fluid parameters, and start-up conditions. The data contained in the file must be entered one item per line in the following order.

Line #1 — - Coded name of the dispersed fluid chosen. This code is found in Table V-1. The code must be in capital letters and occupy the first six spaces of the line. Codes with less than six letters/numbers must have fill spaces following them to account for a total of six spaces in the field.

Line #2 — - Dispersed fluid mass flow rate (kg/sec). Generally this is a decimal quantity.

Line #3 — - Dispersed fluid inlet temperature (°C)

Line #4 — - Dispersed fluid initial droplet/bubble radius (meters). Generally this is a small value such as 1 or 2 mm which would be entered as 0.001 or 0.002.

Line #5 — - Coded name of the continuous fluid chosen. This code is found in Table V-1. The code must be in capital letters and occupy the first six spaces of the line. Codes with less than six letters/numbers must have fill spaces following them to account for a total of six spaces in the field.

Line #6 — - Continuous fluid mass flow rate (kg/sec). Generally this is a decimal quantity.

Line #7   - Continuous fluid inlet temperature (°C)

Line #8   - Continuous fluid quality (dimensionless value of either 0.0

or 1.0). A value of 0.0 indicates a liquid, a value of 1.0

indicates a vapor. The program does not permit the

continuous fluid to change state and will terminate if this

parameter changes within the program.

Line #9   - DCHX column radius (meters)

Line #10   - DCHX column height (meters)

Line #11   - DCHX operating pressure (kPa). This is the nominal

operating pressure at the top of the column. The pressure at

the bottom and throughout the length of the column will be

adjusted for hydrostatic effects.

Line #12   - Dispersed fluid nozzle inlet area (meters). It is assumed

that the dispersed fluid is being introduced through a spray

nozzle. This quantity represents the sum of the areas of the

inlet holes of the nozzle device. The input value will be

evaluated and change this parameter to match the resulting

dispersed fluid velocity near the nozzle. The new value will

be listed in the output.

Line #13   - Number of individual control volumes the column is divided

into for the Runge-Kutta solution. Control volume is a disc

shaped volume equal to the cross sectional area of the

column times the height of the increment. The maximum number is 2000. The minimum must be a reasonable amount (generally 100-200 minimum) to achieve accurate results. The number of control volumes bears directly on the run time. Values less than 300 run reasonably fast. Values above 500 are substantially more expensive if multiple runs are planned. *(Control volumes should be at least as large as the largest anticipated droplet/bubble size.)*

Line #14

First entry - Fluid enthalpy tolerance (J/Kg°C). Tolerance to which program iterates before a solution is reported. This parameter applied to the fluid which is the target of the Runge-Kutta shooting method (i.e. heavy fluid introduced at top of DCHX column). Program calculates enthalpy for the inlet conditions and then references each shooting method iteration. Once solution values fall within the tolerance, the program completes final portions and prints out a solution profile. Generally a value of 0.1 or 0.01 should be used. Smaller values will increase required CPU time.

Second entry - Fluid temperature min/max difference tolerance (°C). Tolerance of bracketed values of shooting method guesses. If subsequent guesses of the starting temperature of the target

fluid changes by less than this parameter then program declares a solution is reached. Generally a value of 0.1 or 0.01 should be used. Smaller values will increase required CPU time.

Line #15

First Entry — Search acceleration index. This parameter governs the way the program searches for temperature guesses in the Runge-Kutta methodology. The values may be 0,1,2, or 3. Generally a value of 0 is used which is sets the search method to a bisection of the temperature interval. For certain combinations of fluids, a coarse initial guess can erroneously eliminate large portions of the interval and prohibit precise solutions. An indication that this is happening occurs in the temperature profiles of one of the fluids. The iterated temperature for the known inlet condition differs from the temperature given in the input file by some value. To correct this occurrence the index is incremented by 1 and the run retried. This is repeated until the inlet temperature from the iterated solution once again agrees with the input value. The maximum value of this index is 3 which represents a slower *shooting guess* sequence. A setting of 3 can double the CPU time required for a run.

Second Entry   - Column heat loss coefficient. A value of 1.0 indicates

no loss of column heat to the outside environment. A

value of 1.1 (for example) indicates a 10% loss of heat

from the continuous fluid to the outside environment.

A value of 1.15 would mean a 15% loss, etc.

Program Compiling

The code is written in FORTRAN 77. All subroutines needed to run the

program are written into the code. No outside library routines are required.

Compiling of the program can be done per normal procedures.

Output Files

Results of the DCHX design code are contained in seven output files -

dxout.dat, dxoutd.dat, dxoutd1.dat, dxoutd2.dat, dxoutc.dat, dxoutc1.dat, and

dxoutfh.dat. The primary output file is "dxout.dat". This file contains a record of

the key input parameters from the dxin.dat input file and resulting DCHX general

performance . This is also where any error messages or limit violations are

recorded. This should be the first file reviewed at the completion of a simulation

run. An example of the output is shown in the appendix. In all cases, the total

output of the DCHX is given. In addition, some analysis is performed. For cases

where the dispersed fluid undergoes a phase change along the length of the

column, the Log Mean Temperature Difference and volumetric heat transfer

coefficient are calculated and recorded. For cases where the dispersed fluid stays

as either a liquid or vapor, the effectiveness is given in accordance with the effectiveness-NTU method of calculation. Additional qualifying information is given about the direction of the heat transfer and the numerical iterations required to run the input specifications.

The remaining six output files contain profile data referenced to the control volume location along the length of the tested DCHX column. Output files containing the letter "d", "d1", and "d2" refer to the dispersed fluid results, "c" and "c1" is for the continuous fluid results. An additional file, "fh" hold generalized data concerning the fluid dynamic parameters and heat transfer coefficients. Reynolds number, Peclect number and drag coefficient are examples of fluid dynamic parameters of interest.

All output is in S.I. units with these units specified at the top of each column where applicable. Examples of the files are contained in this appendix.

Error Treatment

It is likely that during the course of implementing and testing combinations of parameters, the code will fail and return error messages that state mathematical errors have occurred. It is difficult to anticipate all combinations and extremes of the parameters and build in "fixes" or advisory messages. Therefore, it is important that the user be at least somewhat skilled in the engineering aspects of direct contact heat exchangers to understand where the potential source of error lies. Below are guidelines in to aid in trouble shooting an error occurrence.

1. Continuous or dispersed fluid is at a temperature outside of the range of

the data that went into constructing the curve fits of the thermodynamic and thermophysical properties. The user must adjust parameters such that the fluid operates at a higher or lower temperature.

2. The fluids selected are not buoyant enough to each other.

3. The dispersed fluid nozzle area is too small or too large for the flow rate specified. This causes entry of the fluid to act as either a jet or ooze instead of normal buoyant flow. Adjust this value up by a factor of 2 to 10 as a first attempt at overcoming a mathematical error.
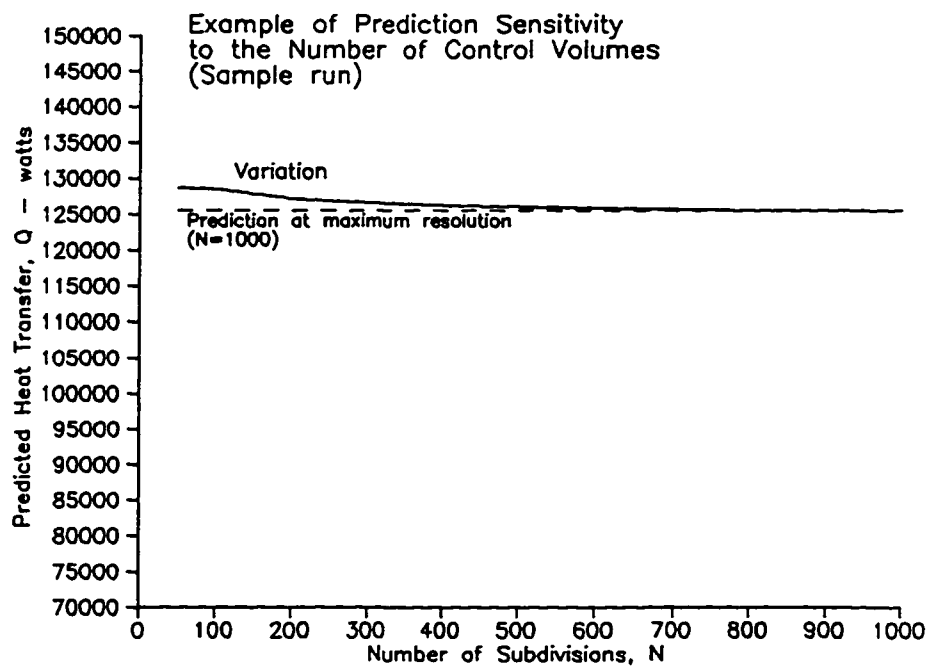
Figure V-1 Numerical Sensitivity to Control Volume Resolution.

Table V-1 Fluids Listing

Fluid/Gas	Code used to specify fluid in input file	Temperature Range °C	Notes
1. Water	H2O	0 < T < 700	
Hydrocarbons			
2. Butane	BUT	Limits unknown	
3. Ethylene	ETHYL	-165 < T < 225	
4. Heptane	HEP	-90 < T < 400	
5. Isobutane	ISOB	Limits unknown	
6. Isopentane	ISOP	Limits unknown	
7. Methane	METH	-173 < T < 83	
8. Pentane	PENT	0 < T < 200	
Refrigerants			
9. R-11	F11	0 < T < 150	
10. R-13	F13	0 < T < 100	
11. R-22	F22	-20 < T < 60	
12. R-23	F23	-40 < T < 10	
13. R-113	F113	0 < T < 170	
14. R-114	F114	-40 < T < 115	
Heat Transfer Fluids			
15. Therminol® 44	TH44	-45 < T < 260	
16. Therminol® 55	TH55	0 < T < 343	
17. Therminol® 60	TH60	-59 < T < 343	
18. Therminol® 66	TH66	-18 < T < 371	
19. Therminol® 88	TH88	149 < T < 482	
20. Therminol® VP-1	MTHVP1	15 < T < 404	
21. DOWTHERM SR-1	DWTHSR1	0 < T < 125	
22. DOWTHERM 4000	DT4000	4 < T < 177	
23. DOWTHERM 4000, 30% Glycol	DT4030	4 < T < 176	
24. DOWTHERM 4000, 40% Glycol	DT4040	4 < T < 176	
25. DOWTHERM 4000, 50% Glycol	DT4050	4 < T < 176	
26. DOWTHERM 4000, 60% Glycol	DT4060	4 < T < 176	
27. DOWFROST	DWFRST	4 < T < 121	
28. DOWFROST HD	DWFHD	4 < T < 177	
29. DOWFROST HD, 30% Glycol	DFHD30	4 < T < 162	

30.	DOWFROST HD, 40% Glycol	DFHD40	4 < T < 162	
31.	DOWFROST HD, 50% Glycol	DFHD50	4 < T < 162	
32.	DOWFROST HD, 60% Glycol	DFHD60	4 < T < 162	
33.	THERMALANE® 550	THM550	-17 < T < 316	
34.	THERMALANE® 600	THM600	-17 < T < 327	
35.	THERMALANE® 800	THM800	-17 < T < 371	
36.	Paratherm NF	PARANF	10 < T < 316	
37.	Paratherm HE	PARAHE	10 < T < 316	
38.	CALFLO AF	CFAF	40 < T < 316	
39.	CALFLO FG	CFFG	40 < T < 288	
40.	CALFLO HTF	CFHTF	40 < T < 316	
41.	SYLTHERM® 800	SYLTH8	-73 < T < 260	
42.	Thermex®	THRMX		

Miscellaneous Oils

43.	Engine Oil (Unused)	ENG	0 < T < 156	
44.	KhF22 Oil (Standard 5546-66)	KHF22	Limits unknown	
45.	MS-20 Oil	MS20	Limits unknown	
46.	Transformer Oil (Standard 982-68)	TRAN	Limits unknown	
47.	VM-4 Oil (Standard 7903-56)	VM4	-30 < T < 100	
48.	TM-1 (VTU-M3-11-62)	TM1	-50 < T < 100	

Gases

49.	Air	AIR	-173 < T < 2726	
50.	Ammonia (NH_3)	NH3	26 < T < 306	
51.	Carbon Dioxide (CO_2)	CO2	-53 < T < 1526	
52.	Hydrogen (H_2)	H2	-173 < T < 1726	
53.	Nitrogen (N_2)	N2	-173 < T < 1026	
54.	Oxygen (O_2)	O2	-173 < T < 1026	

Miscellaneous Fluids

55.	Ethylene Glycol [$C_2H_4(OH)_2$]	ETHYLG	0 < T < 100	
56.	Glycerin [$C_3H_5(OH)_3$]	GLYCRN	0 < T < 46	
57.	Mercury (Hg)	HG	0 < T < 326	

Sample Input File - dxin.dat

```
PENT                 DISPERSED FLUID
0.21                     Dispersed flow rate (kg/sec)
41.0                     Dispersed inlet temperature (°C)
0.002                    Initial dispersed droplet radius (m)
H2O                  CONTINUOUS FLUID
1.91                     Continuous flow rate (kg/sec)
85.0                     Continuous inlet temperature (°C)
0.0                      Continuous fluid quality
.305                 DCHX radius (m)
3.0                  DCHX length (m)
260.0                DCHX pressure (kPa)
.1                   DCHX dispersed fluid nozzle inlet area (m²)
150                  Numerical resolution
0.01 0.01            Enthalpy and Temperature check tolerance
0 1.1 1              Search accel. index, Heat loss coef., Progress
flag
```

DATAFILE: dxout.dat

Input Values

```
        Heat Exchanger Length:      3.00 meters
        Heat Exchanger Radius:      0.50 meters
   Nominal Operating Pressure:    260.00 kPa
```

```
                    Dispersed Fluid    Continuous Fluid
            Fluid:       PENT                H2O
   Mass Flow Rate:      0.1200              1.9100     kg/sec
       Inlet Temp:      41.00              85.00       deg C
```

Disp. Fld. Droplet/Bubble Radius: .002000 meters
          Continuous Fluid Quality: 0.

DCHX Parameter Profile

```
     Fluid Flow Configuration:  1
   Temperature Configuration:   1
   Total Device Heat Trans   D:        39125. Watts
   Total Device Heat Trans   C:       -47341. Watts
```

```
Dispersed Fluid Temp @ z=0:     41.0 deg C
Dispersed Fluid Temp @ z=N:     73.0 deg C
Continuous Fluid Temp @z=0:     77.6 deg C
Continuous Fluid Temp @z=N:     85.0 deg C
```

```
   Log Mean Temp Difference:    22.09   deg C
                 Parallelism:    0.0000
   Optimal Fluid Usage Ind.:    0.0000
   Volumetric Trans Coeff  D:     751.8285 W/m3 K
   Volumetric Trans Coeff  C:     909.7124 W/m3 K
```

```
            Prandtl # (D):   **********
            Prandtl # (C):      2.1524
```

Adjusted Dispersed Fluid Nozzle Area: 0.001

HEAT TRANSFER IS FROM CONTINUOUS FLUID TO DISPERSED FLUID

CONVERGENCE OCCURRED IN 20 ITERATIONS

DATAFILE: dxoutd.dat
DISPERSED FLUID RESULTS
DCHX Configuration = 1
Dispersed Fluid: PENT

Idx i	Loo Z m	Vel(a) Udz m/s	Vel(r) Ud m/s	Temp Td C	Holdup Phi	HtXfer QcvD W	Qual Xd -	D- rad r m	Pop nB
150	3.000	1.717	1.719	73.0	0.014	8.	1.0000	.00917	69.
149	2.980	1.716	1.718	72.9	0.014	9.	1.0000	.00917	69.
148	2.960	1.715	1.718	72.9	0.014	9.	1.0000	.00916	69.
147	2.940	1.714	1.717	72.9	0.014	9.	1.0000	.00916	69.
146	2.920	1.713	1.716	72.8	0.014	9.	1.0000	.00916	69.
145	2.900	1.713	1.715	72.8	0.014	9.	1.0000	.00915	69.
144	2.880	1.712	1.714	72.8	0.014	9.	1.0000	.00915	70.
143	2.860	1.711	1.713	72.7	0.014	9.	1.0000	.00915	70.
142	2.840	1.710	1.713	72.7	0.014	9.	1.0000	.00914	70.
141	2.820	1.709	1.712	72.7	0.014	9.	1.0000	.00914	70.
140	2.800	1.709	1.711	72.6	0.014	9.	1.0000	.00914	70.
139	2.780	1.708	1.710	72.6	0.014	9.	1.0000	.00913	70.
138	2.760	1.707	1.709	72.5	0.014	9.	1.0000	.00913	70.
137	2.740	1.706	1.709	72.5	0.014	9.	1.0000	.00913	70.
136	2.720	1.705	1.708	72.5	0.014	9.	1.0000	.00913	70.
135	2.700	1.705	1.707	72.4	0.014	9.	1.0000	.00912	70.
134	2.680	1.704	1.706	72.4	0.014	9.	1.0000	.00912	70.
133	2.660	1.703	1.705	72.4	0.014	9.	1.0000	.00912	70.
132	2.640	1.702	1.705	72.3	0.014	9.	1.0000	.00911	70.
131	2.620	1.701	1.704	72.3	0.014	9.	1.0000	.00911	70.
130	2.600	1.701	1.703	72.3	0.014	9.	1.0000	.00911	70.
.	.	.	.	.	.	.	.	.	.
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.	.	.	.	.	.	.	.	.	.
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.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
23	0.460	0.137	0.140	64.9	0.002	55.	0.0000	.00203	867.
22	0.440	0.137	0.140	64.7	0.002	56.	0.0000	.00203	867.
21	0.420	0.137	0.140	64.5	0.002	57.	0.0000	.00203	868.
20	0.400	0.137	0.139	64.3	0.002	57.	0.0000	.00203	869.
19	0.380	0.137	0.139	64.1	0.002	58.	0.0000	.00203	870.
18	0.360	0.137	0.139	63.9	0.002	59.	0.0000	.00203	870.
17	0.340	0.137	0.139	63.6	0.002	60.	0.0000	.00203	871.
16	0.320	0.136	0.139	63.4	0.002	61.	0.0000	.00203	872.
15	0.300	0.136	0.139	63.2	0.002	62.	0.0000	.00203	873.
14	0.280	0.136	0.139	62.9	0.002	63.	0.0000	.00202	874.
13	0.260	0.136	0.139	62.7	0.002	64.	0.0000	.00202	875.
12	0.240	0.136	0.138	62.5	0.002	65.	0.0000	.00202	876.
11	0.220	0.136	0.138	62.2	0.002	66.	0.0000	.00202	877.
10	0.200	0.136	0.138	62.0	0.002	67.	0.0000	.00202	877.
9	0.180	0.135	0.138	61.7	0.002	68.	0.0000	.00202	878.
8	0.160	0.135	0.138	61.5	0.002	69.	0.0000	.00202	879.
7	0.140	0.135	0.138	61.2	0.002	71.	0.0000	.00202	880.
6	0.120	0.135	0.137	61.0	0.002	72.	0.0000	.00202	881.
5	0.100	0.135	0.137	60.7	0.002	73.	0.0000	.00202	883.
4	0.080	0.134	0.137	60.0	0.002	210.	0.0000	.00202	885.
3	0.060	0.133	0.136	58.5	0.002	510.	0.0000	.00202	892.
2	0.040	0.132	0.134	55.4	0.002	1046.	0.0000	.00202	905.
1	0.020	0.129	0.131	49.5	0.002	2105.	0.0000	.00201	923.
0	0.000	0.136	0.138	41.0	0.002	170.	0.0000	.00200	877.

DATAFILE: dxoutd1.dat
DISPERSED FLUID PARAMETERS
DCHX Configuration = 1
Dispersed Fluid: PENT

Idx i	Loo Z m	Density rho kg/m3	Viscosity mu Pa-s	Thermal Capacit Cp J/kg K	Cond Coeff k W/m K	Enthalpy Hd J/kg K
150	3.000	6.248	0.79507E-05	1955.0	0.01948	-1178.2
149	2.980	6.254	0.79495E-05	1955.0	0.01948	-1178.3
148	2.960	6.260	0.79484E-05	1954.9	0.01947	-1178.3
147	2.940	6.267	0.79473E-05	1954.8	0.01947	-1178.4
146	2.920	6.273	0.79462E-05	1954.8	0.01947	-1178.5
145	2.900	6.279	0.79451E-05	1954.7	0.01946	-1178.6
144	2.880	6.286	0.79440E-05	1954.7	0.01946	-1178.7
143	2.860	6.292	0.79428E-05	1954.6	0.01945	-1178.7
142	2.840	6.298	0.79417E-05	1954.5	0.01945	-1178.8
141	2.820	6.305	0.79406E-05	1954.5	0.01944	-1178.9
140	2.800	6.311	0.79395E-05	1954.4	0.01944	-1179.0
139	2.780	6.317	0.79383E-05	1954.4	0.01944	-1179.1
138	2.760	6.324	0.79372E-05	1954.3	0.01943	-1179.1
137	2.740	6.330	0.79360E-05	1954.2	0.01943	-1179.2
136	2.720	6.336	0.79349E-05	1954.2	0.01942	-1179.3
135	2.700	6.343	0.79337E-05	1954.1	0.01942	-1179.4
134	2.680	6.349	0.79326E-05	1954.1	0.01941	-1179.5
133	2.660	6.355	0.79314E-05	1954.0	0.01941	-1179.5
132	2.640	6.362	0.79303E-05	1953.9	0.01941	-1179.6
131	2.620	6.368	0.79291E-05	1953.9	0.01940	-1179.7
130	2.600	6.375	0.79280E-05	1953.8	0.01940	-1179.8
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.	.	.	.	.	.	.
.	.	.	.	.	.	.
22	0.440	578.310	0.15578E-03	2486.9	0.10420	-1525.9
21	0.420	578.524	0.15604E-03	2486.1	0.10427	-1526.5
20	0.400	578.740	0.15631E-03	2485.2	0.10434	-1527.0
19	0.380	578.961	0.15657E-03	2484.4	0.10441	-1527.5
18	0.360	579.184	0.15685E-03	2483.5	0.10448	-1528.1
17	0.340	579.411	0.15712E-03	2482.6	0.10455	-1528.6
16	0.320	579.642	0.15740E-03	2481.7	0.10463	-1529.2
15	0.300	579.876	0.15768E-03	2480.8	0.10470	-1529.7
14	0.280	580.114	0.15797E-03	2479.8	0.10478	-1530.3
13	0.260	580.355	0.15826E-03	2478.9	0.10485	-1530.9
12	0.240	580.600	0.15856E-03	2477.9	0.10493	-1531.5
11	0.220	580.849	0.15886E-03	2477.0	0.10501	-1532.1
10	0.200	581.102	0.15916E-03	2476.0	0.10508	-1532.7
9	0.180	581.359	0.15947E-03	2475.0	0.10516	-1533.3
8	0.160	581.620	0.15979E-03	2474.0	0.10524	-1533.9
7	0.140	581.885	0.16011E-03	2473.0	0.10532	-1534.6
6	0.120	582.154	0.16043E-03	2472.0	0.10541	-1535.2
5	0.100	582.428	0.16076E-03	2471.0	0.10549	-1535.9
4	0.080	583.086	0.16156E-03	2468.5	0.10569	-1537.5
3	0.060	584.653	0.16347E-03	2462.7	0.10615	-1541.3
2	0.040	587.767	0.16737E-03	2451.6	0.10704	-1548.9
1	0.020	593.644	0.17565E-03	2432.1	0.10863	-1563.3
0	0.000	601.951	0.19100E-03	2408.0	0.11076	-1583.9

```
DATAFILE:   dxoutd2.dat
DISPERSED DROPLET/BUBBLE INFO
Dispersed Fluid:  PENT
```

i	Z	hT	hS	hTS	hST	hBB	h
150	3.000	0.0	0.0	0.0	19233.2	10.6	10.6
149	2.980	0.0	0.0	0.0	19230.1	10.6	10.6
148	2.960	0.0	0.0	0.0	19226.9	10.6	10.6
147	2.940	0.0	0.0	0.0	19223.8	10.6	10.6
146	2.920	0.0	0.0	0.0	19220.7	10.6	10.6
145	2.900	0.0	0.0	0.0	19217.6	10.6	10.6
144	2.880	0.0	0.0	0.0	19214.4	10.6	10.6
143	2.860	0.0	0.0	0.0	19211.3	10.6	10.6
142	2.840	0.0	0.0	0.0	19208.2	10.6	10.6
141	2.820	0.0	0.0	0.0	19205.1	10.6	10.6
140	2.800	0.0	0.0	0.0	19201.9	10.6	10.6
139	2.780	0.0	0.0	0.0	19198.8	10.6	10.6
138	2.760	0.0	0.0	0.0	19195.7	10.6	10.6
137	2.740	0.0	0.0	0.0	19192.5	10.6	10.6
136	2.720	0.0	0.0	0.0	19189.4	10.6	10.6
135	2.700	0.0	0.0	0.0	19186.3	10.6	10.6
134	2.680	0.0	0.0	0.0	19183.2	10.6	10.6
133	2.660	0.0	0.0	0.0	19180.0	10.6	10.6
132	2.640	0.0	0.0	0.0	19176.9	10.6	10.6
131	2.620	0.0	0.0	0.0	19173.8	10.6	10.6
130	2.600	0.0	0.0	0.0	19170.6	10.6	10.6
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25	0.500	2494.1	101.4	97.4	19233.1	0.0	97.4
24	0.480	2493.6	101.5	97.5	19233.1	0.0	97.5
23	0.460	2493.1	101.5	97.6	19233.1	0.0	97.6
22	0.440	2492.6	101.6	97.7	19233.1	0.0	97.7
21	0.420	2492.1	101.7	97.7	19233.1	0.0	97.7
20	0.400	2491.5	101.8	97.8	19233.1	0.0	97.8
19	0.380	2491.0	101.9	97.9	19233.1	0.0	97.9
18	0.360	2490.4	102.0	98.0	19233.1	0.0	98.0
17	0.340	2489.8	102.1	98.1	19233.1	0.0	98.1
16	0.320	2489.3	102.2	98.2	19233.1	0.0	98.2
15	0.300	2488.7	102.3	98.2	19233.1	0.0	98.2
14	0.280	2488.1	102.4	98.3	19233.1	0.0	98.3
13	0.260	2487.5	102.5	98.4	19233.1	0.0	98.4
12	0.240	2486.9	102.6	98.5	19233.1	0.0	98.5
11	0.220	2486.2	102.7	98.6	19233.1	0.0	98.6
10	0.200	2485.6	102.8	98.7	19233.1	0.0	98.7
9	0.180	2484.9	102.9	98.8	19233.1	0.0	98.8
8	0.160	2484.3	103.0	98.9	19233.1	0.0	98.9
7	0.140	2483.6	103.1	98.9	19233.1	0.0	98.9
6	0.120	2482.9	103.1	99.0	19233.1	0.0	99.0
5	0.100	2482.1	103.2	99.1	19233.1	0.0	99.1
4	0.080	2480.1	103.4	99.3	19233.1	0.0	274.9
3	0.060	2475.6	103.9	99.7	19233.1	0.0	616.0
2	0.040	2466.8	104.9	100.6	19233.1	0.0	1089.1
1	0.020	2455.5	107.6	103.1	19233.1	0.0	1733.0
0	0.000	2503.9	121.6	116.0	19233.1	0.0	116.0

```
DATAFILE:   dxoutc.dat
CONTINUOUS FLUID RESULTS
DCHX Configuration = 1
Continuous Fluid:   H20
```

Idx i	Loc Z	Vel Uc m/s	Temp Tc C	HtXfer QcvC W	1-Phi	Press P kPa
150	3.000	-0.00255	85.0	-10.	0.9858	231.67
149	2.980	-0.00255	85.0	-10.	0.9858	231.86
148	2.960	-0.00255	85.0	-10.	0.9858	232.05
147	2.940	-0.00255	85.0	-10.	0.9858	232.23
146	2.920	-0.00255	85.0	-10.	0.9858	232.42
145	2.900	-0.00255	85.0	-10.	0.9858	232.61
144	2.880	-0.00255	85.0	-10.	0.9858	232.80
143	2.860	-0.00255	85.0	-10.	0.9858	232.98
142	2.840	-0.00255	85.0	-11.	0.9858	233.17
141	2.820	-0.00255	85.0	-11.	0.9858	233.36
140	2.800	-0.00255	85.0	-11.	0.9858	233.55
139	2.780	-0.00255	85.0	-11.	0.9858	233.73
138	2.760	-0.00255	85.0	-11.	0.9858	233.92
137	2.740	-0.00255	85.0	-11.	0.9859	234.11
136	2.720	-0.00255	85.0	-11.	0.9859	234.30
135	2.700	-0.00255	85.0	-11.	0.9859	234.48
134	2.680	-0.00255	85.0	-11.	0.9859	234.67
133	2.660	-0.00255	85.0	-11.	0.9859	234.86
132	2.640	-0.00255	85.0	-11.	0.9859	235.05
131	2.620	-0.00255	85.0	-11.	0.9859	235.23
130	2.600	-0.00255	85.0	-11.	0.9859	235.42
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.	.	.	.	.	.	.
23	0.460	-0.00250	78.7	-66.	0.9981	255.61
22	0.440	-0.00250	78.7	-67.	0.9981	255.80
21	0.420	-0.00250	78.7	-68.	0.9981	255.99
20	0.400	-0.00250	78.7	-69.	0.9981	256.19
19	0.380	-0.00250	78.7	-71.	0.9981	256.38
18	0.360	-0.00250	78.7	-72.	0.9981	256.57
17	0.340	-0.00250	78.6	-73.	0.9981	256.76
16	0.320	-0.00250	78.6	-74.	0.9981	256.95
15	0.300	-0.00250	78.6	-75.	0.9981	257.14
14	0.280	-0.00250	78.6	-76.	0.9981	257.33
13	0.260	-0.00250	78.6	-78.	0.9981	257.52
12	0.240	-0.00250	78.6	-79.	0.9981	257.71
11	0.220	-0.00250	78.6	-80.	0.9981	257.90
10	0.200	-0.00250	78.6	-81.	0.9981	258.09
9	0.180	-0.00250	78.6	-83.	0.9981	258.28
8	0.160	-0.00250	78.5	-84.	0.9981	258.47
7	0.140	-0.00250	78.5	-85.	0.9981	258.66
6	0.120	-0.00250	78.5	-87.	0.9981	258.86
5	0.100	-0.00250	78.5	-88.	0.9981	259.05
4	0.080	-0.00250	78.5	-254.	0.9981	259.24
3	0.060	-0.00250	78.4	-617.	0.9980	259.43
2	0.040	-0.00250	78.3	-1266.	0.9980	259.62
1	0.020	-0.00250	78.0	-2547.	0.9980	259.81
0	0.000	-0.00250	77.6	-206.	0.9981	260.00

DATAFILE: dxoutc1.dat
CONTINUOUS FLUID PARAMETERS
DCHX Configuration = 1
Continuous Fluid: H2O

Idx i	Loc Z m	Density rho kg/m3	Viscosity mu Pa-s	Thermal Capacit Cp J/kg K	Cond Coeff k W/m K	Enthalpy Hd J/kg K
150	3.000	968.704	0.32794E-03	4199.1	0.67218	356.0
149	2.980	968.705	0.32795E-03	4199.1	0.67218	356.0
148	2.960	968.706	0.32795E-03	4199.1	0.67218	356.0
147	2.940	968.707	0.32795E-03	4199.1	0.67218	356.0
146	2.920	968.708	0.32796E-03	4199.1	0.67218	356.0
145	2.900	968.709	0.32796E-03	4199.1	0.67218	356.0
144	2.880	968.710	0.32796E-03	4199.1	0.67218	356.0
143	2.860	968.711	0.32796E-03	4199.1	0.67218	356.0
142	2.840	968.712	0.32797E-03	4199.1	0.67218	356.0
141	2.820	968.713	0.32797E-03	4199.1	0.67218	356.0
140	2.800	968.714	0.32797E-03	4199.1	0.67218	356.0
139	2.780	968.715	0.32798E-03	4199.1	0.67218	356.0
138	2.760	968.716	0.32798E-03	4199.1	0.67217	356.0
137	2.740	968.717	0.32798E-03	4199.1	0.67217	356.0
136	2.720	968.718	0.32798E-03	4199.1	0.67217	355.9
135	2.700	968.720	0.32799E-03	4199.1	0.67217	355.9
134	2.680	968.721	0.32799E-03	4199.1	0.67217	355.9
133	2.660	968.722	0.32799E-03	4199.1	0.67217	355.9
132	2.640	968.723	0.32800E-03	4199.1	0.67217	355.9
131	2.620	968.724	0.32800E-03	4199.1	0.67217	355.9
130	2.600	968.725	0.32800E-03	4199.1	0.67217	355.9
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.	.	.	.	.	.	.
22	0.440	972.700	0.35489E-03	4193.5	0.66830	329.6
21	0.420	972.706	0.35493E-03	4193.5	0.66830	329.6
20	0.400	972.712	0.35497E-03	4193.5	0.66829	329.5
19	0.380	972.718	0.35501E-03	4193.5	0.66828	329.5
18	0.360	972.724	0.35505E-03	4193.5	0.66828	329.4
17	0.340	972.731	0.35510E-03	4193.5	0.66827	329.4
16	0.320	972.737	0.35514E-03	4193.5	0.66826	329.3
15	0.300	972.743	0.35519E-03	4193.5	0.66826	329.3
14	0.280	972.750	0.35523E-03	4193.5	0.66825	329.3
13	0.260	972.756	0.35528E-03	4193.4	0.66824	329.2
12	0.240	972.763	0.35533E-03	4193.4	0.66824	329.2
11	0.220	972.770	0.35538E-03	4193.4	0.66823	329.1
10	0.200	972.777	0.35543E-03	4193.4	0.66822	329.1
9	0.180	972.784	0.35548E-03	4193.4	0.66822	329.0
8	0.160	972.791	0.35553E-03	4193.4	0.66821	329.0
7	0.140	972.798	0.35558E-03	4193.4	0.66820	328.9
6	0.120	972.806	0.35563E-03	4193.4	0.66819	328.9
5	0.100	972.813	0.35569E-03	4193.4	0.66819	328.8
4	0.080	972.831	0.35582E-03	4193.4	0.66817	328.7
3	0.060	972.874	0.35614E-03	4193.3	0.66812	328.4
2	0.040	972.959	0.35678E-03	4193.2	0.66803	327.8
1	0.020	973.119	0.35800E-03	4193.0	0.66786	326.8
0	0.000	973.348	0.35976E-03	4192.7	0.66761	325.2

DATAFILE: dxoutfh.dat
FLUID AND HEAT TRANSFER VALUES
DCHX Configuration = 1

Idx	Loc Z m	Reynolds Number Re	Peclect Number Pe	Drag Coeff Cd	Ht Xfer Coeff h W/m2 K
150	3.000	93075.	190767.	0.283E+00	10.6
149	2.980	92999.	190614.	0.283E+00	10.6
148	2.960	92924.	190461.	0.283E+00	10.6
147	2.940	92849.	190308.	0.283E+00	10.6
146	2.920	92773.	190156.	0.283E+00	10.6
145	2.900	92698.	190004.	0.283E+00	10.6
144	2.880	92623.	189852.	0.283E+00	10.6
143	2.860	92548.	189699.	0.283E+00	10.6
142	2.840	92473.	189548.	0.283E+00	10.6
141	2.820	92398.	189396.	0.283E+00	10.6
140	2.800	92323.	189244.	0.283E+00	10.6
139	2.780	92248.	189093.	0.283E+00	10.6
138	2.760	92174.	188942.	0.283E+00	10.6
137	2.740	92099.	188790.	0.283E+00	10.6
136	2.720	92024.	188639.	0.283E+00	10.6
135	2.700	91950.	188488.	0.283E+00	10.6
134	2.680	91875.	188338.	0.283E+00	10.6
133	2.660	91801.	188187.	0.283E+00	10.6
132	2.640	91726.	188036.	0.283E+00	10.6
131	2.620	91652.	187886.	0.283E+00	10.6
130	2.600	91578.	187735.	0.283E+00	10.6
.	.	.	.	.	.
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.	.	.	.	.	.
.	.	.	.	.	.
23	0.460	1552.	3460.	0.433E+00	97.6
22	0.440	1551.	3456.	0.433E+00	97.7
21	0.420	1549.	3453.	0.434E+00	97.7
20	0.400	1547.	3450.	0.434E+00	97.8
19	0.380	1545.	3446.	0.434E+00	97.9
18	0.360	1544.	3442.	0.434E+00	98.0
17	0.340	1542.	3439.	0.434E+00	98.1
16	0.320	1540.	3435.	0.434E+00	98.2
15	0.300	1538.	3432.	0.434E+00	98.2
14	0.280	1536.	3428.	0.435E+00	98.3
13	0.260	1534.	3424.	0.435E+00	98.4
12	0.240	1532.	3420.	0.435E+00	98.5
11	0.220	1530.	3416.	0.435E+00	98.6
10	0.200	1528.	3412.	0.435E+00	98.7
9	0.180	1526.	3408.	0.435E+00	98.8
8	0.160	1524.	3404.	0.436E+00	98.9
7	0.140	1522.	3400.	0.436E+00	98.9
6	0.120	1519.	3395.	0.436E+00	99.0
5	0.100	1514.	3390.	0.436E+00	99.1
4	0.080	1502.	3379.	0.437E+00	274.9
3	0.060	1479.	3352.	0.438E+00	616.0
2	0.040	1444.	3300.	0.441E+00	1089.1
1	0.020	1508.	3225.	0.440E+00	1733.0
0	0.000	1495.	3377.	0.000E+00	116.0

APPENDIX VI

PROGRAM LISTING FOR ONE-DIMENSIONAL SIMULATION

```
C     PROGRAM TO SIMULATE A DIRECT CONTACT HEAT EXCHANGER
C     RICHARD BRICKMAN - DECEMBER 1995
C
      REAL  UD(0:2001),UC(0:2001),TD(0:2001),TC(0:2001),
     #      HUR(0:2001),DENSD(0:2001),DENSC(0:2001),HD(0:2001),
     #      HC(0:2001),R(0:2001),QCV(0:2001),XD(0:2001),P(0:2001),
     #      XC(0:2001),CKC(0:1),VISC(0:1),BET(0:2001),H(0:2001),
     #      HS(0:2001),HT(0:2001),ALPHC(0:2001),VISCD(0:2001),
     #      RYNLD(0:2001),COEFD(0:2001),PEC(0:2001),HCB(0:2001),
     #      CPPC(0:2001),CPPD(0:2001),CKKC(0:2001),CKKD(0:2001),
     #      WG(0:2001),HM(0:2001),DIFF(0:2001),ALPHD(0:2001),
     #      VISCC(0:2001),QCV2(0:2001),HSTAG(0:2001),BPOP(0:2001),
     #      HBB(0:2001),HST(0:2001),UDZ(0:2001)
      INTEGER TCNFIG
      COMMON/HHH/H,HS,HT,HCB,HBB,HST
      COMMON/ARRY/UDZ,UD,UC,TD,TC,P,HUR,DENSD,DENSC,HD,HC,R,QCV,
     #      DZ,XD,BET,CPPC,CPPD,CKKD,CKKC,PEC,VISCD,VISC,RYNLD,
     #      BPOP,VISCC,COEFD,WG,HM,DIFF,QCV2,HSTAG
      COMMON/SCLR/MRD,MRC,TEMPD,TEMPC,RO,PRESS,CQUAL,ICNFIG,TCNFIG,
     #      N,DNZAREA,DXVOLUME,DXLENGTH,DXRADIUS,DFTYPE,CFTYPE
      COMMON/SCLR2/ETA
C
      REAL  MRD,MRC,KP(4),KHD(4),KHC(4),KPC,KHDC,KHCC,NB,MC,MD,GMM,
     #      MT,IMT,MB
      REAL  NUO,NUC
      CHARACTER*6,DFTYPE
      CHARACTER*6,CFTYPE
C
      IF(IFLAGON.EQ.1)PRINT*,'STARTING'
      PI=3.141592654
      G=9.81
      IF(IFLAGON.EQ.1)PRINT*,'FIRST CALCULATIONS'
C
C     DATA INPUT
C          Data is entered into program through an input file that
C             must accompany this coding.
C
      OPEN (UNIT=1, FILE='dxin.dat', STATUS='OLD')
      OPEN (UNIT=2, FILE='dxoutd.dat', STATUS='UNKNOWN')
      OPEN (UNIT=3, FILE='dxoutc.dat', STATUS='UNKNOWN')
      OPEN (UNIT=4, FILE='dxoutfh.dat', STATUS='UNKNOWN')
      OPEN (UNIT=5, FILE='dxoutdl.dat', STATUS='UNKNOWN')
      OPEN (UNIT=6, FILE='dxoutcl.dat', STATUS='UNKNOWN')
      OPEN (UNIT=7, FILE='dxout.dat', STATUS='UNKNOWN')
      OPEN (UNIT=8, FILE='dxoutmt.dat', STATUS='UNKNOWN')
      OPEN (UNIT=9, FILE='dxoutd2.dat', STATUS='UNKNOWN')
      OPEN (UNIT=10, FILE='xport.dat', STATUS='UNKNOWN')
```

150

```
            WRITE(2,*)'DATAFILE:   dxoutd.dat'
            WRITE(3,*)'DATAFILE:   dxoutc.dat'
            WRITE(4,*)'DATAFILE:   dxoutfh.dat'
            WRITE(5,*)'DATAFILE:   dxoutdl.dat'
            WRITE(6,*)'DATAFILE:   dxoutcl.dat'
            WRITE(7,*)'DATAFILE:   dxout.dat'
            WRITE(8,*)'DATAFILE:   dxoutmt.dat'
            WRITE(9,*)'DATAFILE:   dxoutd2.dat'
      C
            IF(IFLAGON.EQ.1)PRINT*,'READING INPUT DATA'
            READ(1,6000)DFTYPE
            READ(1,*)MRD
            READ(1,*)TEMPD
            READ(1,*)RO
            READ(1,6000)CFTYPE
            READ(1,*)MRC
            READ(1,*)TEMPC
            READ(1,*)CQUAL
            CALL FLUIDCAT(DFTYPE,DFCAT,RD)
            CALL FLUIDCAT(CFTYPE,CFCAT,RC)
       6000 FORMAT(A6)
            IF(DFCAT.EQ.3) THEN
                WRITE(7,*)DFTYPE,'UPDATE REQUIRED IN PROGRAM TO RUN THIS
          # DISPERSED FLUID.'
                GOTO 9998
            ELSEIF(CFCAT.EQ.3) THEN
                WRITE(7,*)CFTYPE,'UPDATE REQUIRED IN PROGRAM TO RUN THIS
          # CONTINUOUS FLUID.'
                GOTO 9998
            ENDIF
      C
            READ(1,*)DXRADIUS
            READ(1,*)DXLENGTH
            READ(1,*)PRESS
            READ(1,*)DNZAREA
            READ(1,*)N
            READ(1,*)HTOL,TTOL
            READ(1,*)IAF,ETA
            IFLAGON=0
      C
            IF(IAF.LE.0) ACCELF=1.E20
            IF(IAF.EQ.2) ACCELF=1./.382
            IF(IAF.EQ.3) ACCELF=1./.618
            IF(IAF.GT.3) ACCELF=2.
            IF(N.GT.2000) THEN
                WRITE(7,*)'NUMBER OF DIVISIONS OF COLUMN CANNOT EXCEED 2000'
                GOTO 9998
            ENDIF
      C
            CALL PPRNT
      C
            IF(IFLAGON.EQ.1)PRINT*,'INITIALIZING'
            MD=ABS(MRD)
            MC=ABS(MRC)
            IX=CQUAL
      C
      C
            DZ=DXLENGTH/N
            DXAREA=PI*DXRADIUS**2
            IF(DNZAREA.GT.DXAREA) THEN
                WRITE(7,*)'NOZZLE AREA EXCEEDS COLUMN CROSS SECTION AREA'
                DNZAREA=DXAREA/5.
```

```
      ENDIF
      DXVOLUME=DXAREA*DXLENGTH
      XCCHK=0
C
C     Configuration Check
      IF(IFLAGON.EQ.1)PRINT*,'CHECKING CONFIGURATION'
C
      TGIVEN=TEMPC
      PGIVEN=PRESS
      IF(CFCAT.EQ.1) THEN
          CALL SIFLUID('TP',CFTYPE,TGIVEN,PGIVEN,XCZ,SCZ,HCZ,VCZ,CUZ,
     #          TCZ,PCZ,SLCZ,HLCZ,VLCZ,ULCZ,SVCZ,HVCZ,VVCZ,UVCZ)
          CALL QUALCHCK(XCZ)
      ELSEIF (CFCAT.EQ.2) THEN
          CALL FLTHCAP(CFTYPE,TGIVEN,PGIVEN,CP1,RHOCZ,XCZ,ITRNG)
          CALL TRNGCHK(ITRNG,tgiven)
          VCZ=1./RHOCZ
      ENDIF
      TGIVEN=TEMPD
      PGIVEN=PRESS
      IF(DFCAT.EQ.1) THEN
          CALL SIFLUID('TP',DFTYPE,TGIVEN,PGIVEN,XDZ,SDZ,HDZ,VDZ,DUZ,
     #          TDZ,PDZ,SLDZ,HLDZ,VLDZ,ULDZ,SVDZ,HVDZ,VVDZ,UVDZ)
          CALL QUALCHCK(XDZ)
      ELSEIF (DFCAT.EQ.2) THEN
          CALL FLTHCAP(DFTYPE,TGIVEN,PGIVEN,CP1,RHODZ,XDZ,ITRNG)
          CALL TRNGCHK(ITRNG,tgiven)
          VDZ=1./RHODZ
      ENDIF
C
      IF(VDZ/VCZ.GT.1.) THEN
          ICNFIG=1
      ELSE
          ICNFIG=2
      ENDIF
C
      IF(TEMPC.GT.TEMPD) THEN
          TCNFIG=1
      ELSE
          TCNFIG=2
      ENDIF
C
      IPASS=1
C
C     INITIAL VALUE CALCULATIONS
      IF(IFLAGON.EQ.1)PRINT*,'INITIAL VALUE CALCULATIONS'
C
      IF(ICNFIG.EQ.1) THEN
          TGIVEN=TEMPD
c         PGIVEN=PRESS+G/VCZ*DXLENGTH/1000
          PGIVEN=PRESS
          IF(DFCAT.EQ.1) THEN
              CALL SIFLUID('TP',DFTYPE,TGIVEN,PGIVEN,XDZ,SDZ,HDZ,VDZ,
     #              DUZ,TDZ,PDZ,SLDZ,HLDZ,VLDZ,ULDZ,SVDZ,HVDZ,VVDZ,UVDZ)
              CALL QUALCHCK(XDZ)
              HD(0)=HDZ
              TD(0)=TDZ
              DENSD(0)=1./VDZ
          ELSEIF(DFCAT.EQ.2) THEN
              CALL FLTHCAP(DFTYPE,TGIVEN,PGIVEN,CP1,RHODZ,XDZ,ITRNG)
              CALL TRNGCHK(ITRNG,tgiven)
              HD(0)=0
```

```
                    TD(0)=TEMPD
                    VDZ=1/RHODZ
                    DENSD(0)=RHODZ
                ENDIF
                XD(0)=XDZ
                MRC=-ABS(MRC)
                MRD=ABS(MRD)
                R(0)=RO
            ELSE
                TGIVEN=TEMPC
C                PGIVEN=PRESS+G/VCZ*DXLENGTH/1000
                PGIVEN=PRESS
                IF(CFCAT.EQ.1) THEN
                    CALL SIFLUID('TP',CFTYPE,TGIVEN,PGIVEN,XCZ,SCZ,HCZ,VCZ,CUZ,
     #               TCZ,PCZ,SLCZ,HLCZ,VLCZ,ULCZ,SVCZ,HVCZ,VVCZ,UVCZ)
                    CALL QUALCHCK(XCZ)
                    HC(0)=HCZ
                    TC(0)=TCZ
                    DENSC(0)=1./VCZ
                ELSEIF(CFCAT.EQ.2) THEN
                    CALL FLTHCAP(CFTYPE,TGIVEN,PGIVEN,CP1,RHOCZ,XCZ,ITRNG)
                    CALL TRNGCHK(ITRNG,tgiven)
                    HC(0)=0
                    TC(0)=TEMPC
                    VCZ=1/RHOCZ
                    DENSC(0)=RHOCZ
                ENDIF
                XC(0)=XCZ
                MRD=-ABS(MRD)
                MRC=ABS(MRC)
                RN=RO
                DENSCG=DENSC(0)
            ENDIF
C
C
C       SHOOTING METHOD INITIALIZATION
        IF(IFLAGON.EQ.1)PRINT*,'INITIALIZE SHOOTING METHOD'
C          Bisection using the continuous and dispersed fluid
C          input temperatures as the starting upper and lower limits.
C
        ICOUNT=0
C
        IF(TEMPC.GT.TEMPD) THEN
            TUPPER=TEMPC
            TLOWER=TEMPD
        ELSE
            TUPPER=TEMPD
            TLOWER=TEMPC
        ENDIF
        ITLIM=1
C
C   BEGIN ITERATION FOR SHOOTING METHOD
        IF(IFLAGON.EQ.1)PRINT*,'BEGIN SHOOTING ITERATION'
C
 11     IF(IFLAGON.EQ.1)PRINT*,ICOUNT,'-',I-1
        ICOUNT=ICOUNT+1
        PRINT*,'ITERATION ',ICOUNT
 1      IF(XCCHK.EQ.1) GOTO 2
        IF(ABS(TUPPER-TLOWER).LE.TTOL) THEN
            IF(ICNFIG.EQ.1)THEN
                WRITE(*,*)'COULD NOT FIND SUITABLE INITIAL TC(0)'
                WRITE(7,*)'COULD NOT FIND SUITABLE INITIAL TC(0)'
```

```
          ELSE
              WRITE(*,*)'COULD NOT FIND SUITABLE INITIAL TD(0)'
              WRITE(7,*)'COULD NOT FIND SUITABLE INITIAL TD(0)'
          ENDIF
          GOTO 9998
          ENDIF
2         IF(ICNFIG.EQ.1) THEN
              TC(0)=(TUPPER+TLOWER)/2.
          ELSE
              TD(0)=(TUPPER+TLOWER)/2.
          ENDIF
C
C         Iteration dependent initial values
          IF(IFLAGON.EQ.1)PRINT*,'ITERATION DEPENDENT INITIAL VALUE CALC'
C
          IF(ICNFIG.EQ.1) THEN
c             P(0)=PRESS+(MD*DENSD(0)+MC/VCZ)/(MC+MD)*DXLENGTH*G/1000.
              P(0)=PRESS
              TGIVEN=TC(0)
              PGIVEN=P(0)
              IF(CFCAT.EQ.1) THEN
                  CALL SIFLUID('TP',CFTYPE,TGIVEN,PGIVEN,XC(0),SC,HC(0),VC,
     #                 UIC,TC(0),PC,SLC,HLC,VLC,ULC,SVC,HVC,VVC,UVC)
                  CALL QUALCHCK(XC(0))
              ELSEIF(CFCAT.EQ.2) THEN
                  CALL FLTHCAP(CFTYPE,TGIVEN,PGIVEN,CP1,DENSC(0),XC(0),ITRNG)
                  CALL TRNGCHK(ITRNG,tgiven)
              ENDIF
              IF(CFCAT.EQ.2) GOTO 5
              IF(XCCHK.EQ.1) GOTO 5
              IF(XC(0).NE.CQUAL)THEN
                  IF(TCNFIG.EQ.1) THEN
                      PGIVEN=P(0)
                      XGIVEN=CQUAL
                      CALL SIFLUID('PX',CFTYPE,PGIVEN,XGIVEN,XCX,SCX,HCX,
     #                     VCX,UICX,TLOWER,PCX,SLCX,HLCX,VLCX,ULCX,SVCX,
     #                     HVCX,VVCX,UVCX)
                      GOTO 1
                  ELSE
                      PGIVEN=P(0)
                      XGIVEN=CQUAL
                      CALL SIFLUID('PX',CFTYPE,PGIVEN,XGIVEN,XCX,SCX,HCX,
     #                     VCX,UICX,TUPPER,PCX,SLCX,HLCX,VLCX,ULCX,SVCX,
     #                     HVCX,VVCX,UVCX)
                      GOTO 1
                  ENDIF
              ENDIF
5             xcchk=1
              IF(CFCAT.EQ.1) DENSC(0)=1./VC
              IF(CFCAT.EQ.2) HC(0)=0.0
          ELSE
              P(0)=PRESS
c             P(0)=PRESS+(MC*DENSC(0)+MD/VDZ)/(MD+MC)*G*DXLENGTH/1000.
              TGIVEN=TD(0)
              PGIVEN=P(0)
              IF(DFCAT.EQ.1) THEN
                  CALL SIFLUID('TP',DFTYPE,TGIVEN,PGIVEN,XD(0),SD,HD(0),VD,
     #                 UID,TD(0),PD,SLD,HLD,VLD,ULD,SVD,HVD,VVD,UVD)
                  CALL QUALCHCK(XD(0))
                  DENSD(0)=1./VD
                  IF(VLD*VVD.NE.0) THEN
                      RHODL=1./VLD
```

```
                    RHODV=1./VVD
                 ENDIF
              ELSEIF(DFCAT.EQ.2) THEN
                 CALL FLTHCAP(DFTYPE,TGIVEN,PGIVEN,CP1,DENSD(0),XD(0),ITRNG)
                 CALL TRNGCHK(ITRNG,tgiven)
                 HD(0)=0.0
              ENDIF
           ENDIF
C
C       GUESS OF DISPERSED FLUID VELOCITY AT LOCATION Z=0
C
        IF(ICOUNT.EQ.1) THEN
           UDZ(0)=MRD/DENSD(0)/DNZAREA
        ELSE
           DO 92 IUI=10,1,-1
              IF(UDZ(IUI).NE.0.) THEN
                 UDZ(0)=UDZ(IUI)
                 GOTO 91
              ENDIF
92         CONTINUE
91         DNZAREA=MRD/DENSD(0)/UDZ(0)
        ENDIF
        PHI=MRD/DENSD(0)/UDZ(0)/DXAREA
        HUR(0)=PHI
        IF(ICNFIG.EQ.2) R(0)=RN*(1/DENSD(0)/VDZ)**(1./3.)
        UC(0)=MRC/(1-HUR(0))/DXAREA/DENSC(0)
        UDPR=0.
        UCPR=0.
        IF(XD(0).GE.1.) IXDREF=1
        IF((2*R(0)).LT.DZ) THEN
           NB0=DXAREA*DZ*PHI/(4./3.*PI*R(0)**3.)
        ELSE
           CVIN=2*R(0)/DZ
           NB0=DXAREA*DZ*CVIN*PHI/(4./3.*PI*R(0)**3.)
        ENDIF
        NB=NB0
        BPOP(0)=NB0
        WG(0)=0.0
        MB=DENSD(0)*4./3.*PI*R(0)**3
        DMB=0
C
C   SOLUTION OF DIFFERENTIAL EQUATIONS AND Z (LOCATION) DEPENDENT
C   VARIABLES ALONG LENGTH OF COLUMN
C
        IF(IFLAGON.EQ.1)PRINT*,'MARCHING FOR SOLUTION'
        DO 20 I=0,N
C
C   THERMAL CAPACITANCE OF CONTINUOUS FLUID (Cp=dH/dT)
C
        TGIVEN=TC(I)
        PGIVEN=P(I)
        IF(CFCAT.EQ.1) THEN
           CALL SIFLUID('TP',CFTYPE,TGIVEN,PGIVEN,XC2,SC2,HC2,VC2,UC2,
     #        TC2,PC2,SLC2,HLC2,VLC2,ULC2,SVC2,HVC2,VVC2,UVC2)
           TGIVEN=TC(I)-.0001
           PGIVEN=P(I)
           CALL SIFLUID('TP',CFTYPE,TGIVEN,PGIVEN,XC1,SC1,HC1,VC1,UC1,
     #        TC1,PC1,SLC1,HLC1,VLC1,ULC1,SVC1,HVC1,VVC1,UVC1)
           CPC=(HC2-HC1)/.0001*1000
        ELSEIF(CFCAT.EQ.2) THEN
           CALL FLTHCAP(CFTYPE,TGIVEN,PGIVEN,CPC,RHOC,XC1,ITRNG)
           CALL TRNGCHK(ITRNG,tgiven)
```

```
            ENDIF
            CPPC(I)=CPC
C
C   THERMAL CAPACITANCE OF DISPERSED FLUID (Cp=dH/dT)
C      (Generally not needed but found for completeness)
C
            TGIVEN=TD(I)
            PGIVEN=P(I)
            IF(DFCAT.EQ.1) THEN
                CALL SIFLUID('TP',DFTYPE,TGIVEN,PGIVEN,XD2,SD2,HD2,VD2,UD2,
     #           TD2,PC2,SLD2,HLD2,VLD2,ULD2,SVD2,HVD2,VVD2,UVD2)
                TGIVEN=TD(I)-.0001
                PGIVEN=P(I)
                CALL SIFLUID('TP',DFTYPE,TGIVEN,PGIVEN,XD1,SD1,HD1,VD1,UD1,
     #           TD1,PD1,SLD1,HLD1,VLD1,ULD1,SVD1,HVD1,VVD1,UVD1)
                CPD=(HD2-HD1)/.0001*1000.
            ELSEIF(DFCAT.EQ.2) THEN
                CALL FLTHCAP(DFTYPE,TGIVEN,PGIVEN,CPD,RHOD,XD1,ITRNG)
                CALL TRNGCHK(ITRNG,tgiven)
            ENDIF
            CPPD(I)=CPD
C
C   BETA
C
            if(iflagon.eq.1)print*,'Beta'
            IF(XD(I).GT.0.0.AND.XD(I).LT.1.0) THEN
                CALL BBLMIX(RHODL,RHODV,XD(I),BETA)
            ELSEIF(XD(I).LE.0.0) THEN
                BETA=0.0
            ELSEIF(XD(I).GE.1.0) THEN
                BETA=PI
            ENDIF
            IF(BETA.GT.PI) BETA=PI
            BET(I)=BETA
C
            IF(XD(I).GE.1.AND.XD(I-1).LT.1.)IXDREF=I
C
C   PROPERTY EVALUATION
C
            TGIVEN=TD(I)
            PGIVEN=P(I)*1000.
            CALL PROPTY(DFTYPE,TGIVEN,PGIVEN,CKLD,CKVD,VISLD,VISVD,
     #           SIGD,ITRNG)
            CALL TRNGCHK(ITRNG,tgiven)
            TGIVEN=TC(I)
            PGIVEN=P(I)*1000.
            CALL PROPTY(CFTYPE,TGIVEN,PGIVEN,CKC(0),CKC(1),
     #           VISC(0),VISC(1),SIGC,ITRNG)
            CALL TRNGCHK(ITRNG,tgiven)
            VISCC(I)=VISC(IX)
            CKKD(I)=CKLD*(1.-XD(I))+CKVD*XD(I)
            CKKC(I)=CKC(IX)
C
C   ALPHA OF CONTINUOUS AND DISPERSED FLUID
C
            ALPHAC=CKC(IX)/DENSC(I)/CPC
            ALPHC(I)=ALPHAC
            ALPHAD=CKKD(I)/DENSD(I)/CPD
            ALPHD(I)=ALPHAD
C
C   DISPERSED FLUID VISCOSITY
C
```

```
                    VISD=VISLD*(1-XD(I))+VISVD*XD(I)
                    VISCD(I)=VISD
C
                    IF(I.EQ.0) THEN
                        R(I)=R0
                        IREF=I
                        UCPR=0.
                        UDPR=0.
                        PHI=MRD/DENSD(I)/DXAREA/UDZ(I)
                        HUR(I)=PHI
                        UC(I)=MRC/DENSC(I)/(1-PHI)/DXAREA
                        UD(I)=UDZ(I)-UC(I)
                        REC=DENSC(I)*2.*R(I)*ABS(UD(I))/VISC(IX)
                    ELSE
C
C BUBBLE RADIUS
C
                        R(I)=R(IREF)*(DENSD(IREF)/DENSD(I))**(1./3.)
                        IF(WG(I).NE.0.) THEN
                            VOLBUB=4./3.*PI*R(I)**3+WG(I)*MB/DENSCG
                            R(I)=(VOLBUB*3./4./PI)**(1./3.)
                        ENDIF
C
C REYNOLDS NUMBER
C
                        if(iflagon.eq.1)print*,'Reynolds'
                        REC=DENSC(I)*2.*R(I)*ABS(UD(I-1))/VISC(IX)
C
C DRAG COEFFICIENT
C
                        if(iflagon.eq.1)print*,'CD'
                        CD=(24./REC+6./(1+REC**0.5)+0.4)*((1+2*VISC(IX)/3/VISD)
     #                      /(1+VISC(IX)/VISD))
                        COEFD(I)=CD
C
C DISPERSED FLUID RELATIVE VELOCITY
C
                        if(iflagon.eq.1)print*,'Velocity'
                        GOTO 5677
                        DELTARHO=ABS(DENSD(i)-DENSC(i))
                        aMORTON=G*VISC(ix)**4*DELTARHO/DENSC(i)**2/SIGC**3
                        EOTVOS=G*DELTARHO*R(i)**2/SIGC
                        HHHH=4./3.*EOTVOS*aMORTON**(-.149)*(VISD/VISC(ix))**(-.14)
                        IF(HHHH.LE.59.3) THEN
                            aJJJJ=.94*HHHH**.757
                        ELSE
                            aJJJJ=3.42*HHHH**.441
                        ENDIF
                        UD(i)=VISC(ix)/DENSC(i)/2./R(I)*aMORTON**(-.149)
     #                          *(aJJJJ-.857)
                        GOTO 5678
C
C     This part not used anymore in lieu of above new velocity
C     calculation.
 5677                   D=(R(I)**2+R(IREF)**2)/2/R(I)/R(0)
                        TPC=TC(I)+273.15
                        TPD=TD(I)+273.15
                        IF(ICNFIG.EQ.1) THEN
                            u1=1.1547
                            u2=((1-densd(i)/densc(i)*(r(IREF)/r(i))**3)*(2*r(i)
     #                          *g/cd))**0.5
                            u3=D**(5./6.-D/tpc)
```

```
                      u4=((tpc**2+tpd**2)/2/tpc/tpd)**D
                      u5=(cpc*visc(iX)/ckc(iX))**(r(IREF)/1.6/r(i))
                      UD(I)=u1*u2*u3/u4/u5
                  ELSE
                      IF(DENSD(I).GT.DENSC(I)) THEN
                          UD(I)=-ABS((4./3.*(DENSD(I)-DENSC(I))/DENSD(I)
     #                        *2*R(I)*G/CD))**0.5
                      ELSE
                          UD(I)=ABS((4./3.*(DENSD(I)-DENSC(I))/DENSD(I)
     #                        *2*R(I)*G/CD))**0.5
                      ENDIF
                  ENDIF
 5678             UDZ(I)=UD(I)+UC(I-1)
      C
      C DISPERSED FLUID VELOCITY GRADIENT
      C
                  UDPR=(UDZ(I)-UDZ(I-1))/DZ
      C
      C HOLDUP RATIO
      C
                  PHI=MRD/DENSD(I)/DXAREA/UDZ(I)
                  HUR(I)=PHI
      C
      C CONTINUOUS FLUID VELOCITY AND GRADIENT
      C
                  UC(I)=MRC/DENSC(I)/(1-HUR(I))/DXAREA
                  UCPR=(UC(I)-UC(I-1))/DZ
      C
              ENDIF
              RYNLD(I)=REC
              PEC(I)=ABS(UD(I))*2*R(I)/ALPHAC
              PRANDTLD=VISD*CPD/CKKD(I)

      C
      C DROPLET/BUBBLE POPULATION
      C
              IF(2*R(I).GT.DZ) THEN
                  NB=DXAREA*2.*R(I)*PHI/(4./3.*PI*R(I)**3)
              ELSE
                  NB=DXAREA*DZ*PHI/(4./3.*PI*R(I)**3)
              ENDIF
              BPOP(I)=NB
      C
      C HEAT TRANSFER COEFFICIENT
      C
      C-Tochitani et al.
                  if(iflagon.eq.1)print*,'Tochitani'
              HTH=CKC(IX)/2/R(I)*(ABS(UD(I))*2*R(I)/ALPHAC)**(1./3.)
     #              *(0.466194077*(PI-BETA+.5*SIN(2.*BETA))**(2./3.))
      C
              IF(XD(I).LE.0.0)  THEN
      C
      C-Sideman
                  if(iflagon.eq.1)print*,'Sideman'
                  HSH=.00375*ABS(UD(I))*2*R(I)/ALPHAC*(1./(1.+VISC(IX)/
     #              VISLD))*CKLD/2./R(I)
      C-Tochitani/Sideman Series Combination
                  HHTS=HTH*HSH/(HTH+HSH)
      C-Jacobs (Sideman) High Circulation and Decay - Weighted
                  if(iflagon.eq.1)print*,'Jacobs(Sideman)'
      C           HJAC=50+.0085*REC*PRANDTLD**.7*CKC(IX)/2./R(I)
                  VKV=1.-1.45*(2.+3.*VISD/VISC(IX))/(1.+(DENSD(I)*VISD/
```

1
```
#              DENSC(I)/VISC(IX))**.5)*REC**(-.5)
           HJAC=(2.+1.13*(PEC(I)*VKV)**.5)*CKC(IX)/2./R(I)
           HJT=HTH*HJAC/(HTH+HJAC)
           DDNORM=(I-IREF)*DZ/(2.*R(IREF))
           IF(DDNORM.LE.30) THEN
               HH=HTJ*(1.-DDNORM/30.)**2
C              HH=(0.5*HHTS+0.5*HJAC*(1.-DDNORM/10.)**2)
               IF(HH.LT.HHTS) HH=HHTS
           ELSE
               HH=HHTS
           ENDIF
           HCBN=0.
           HBBR=0.
           HFT=0.
        ELSEIF(XD(I).GT.0.0) THEN
C                                              Coban Modification
           if(iflagon.eq.1)print*,'Coban modification'
           HCBN=5.*CKVD/R(I)
#              *(1.-0.466194077*(PI-BETA+.5*SIN(2.*BETA))**(2./3.))
C
C                                      Brickman/Boehm Modification
C                                      Steinberger & Treybal
           if(iflagon.eq.1)print*,'Brickman/Boehm'
           PR=PEC(I)/REC
           CALL H2OBETA(TC(I),CBeta)
           GR=9.81*CBeta*ABS(TD(I)-TC(I))*(2*R(I))**3/(VISC(IX)/
#              DENSC(I))
           NUO=2.+.569*(GR*PR)**.25
           NUC=NUO+.347*REC**.62*PR**.31
           HSTR=NUC*CKC(IX)/2./R(I)
           HBBR=5.*HSTR*CKVD/(5.*CKVD+R(I)*HSTR)
#              *(1.-0.466194077*(PI-BETA+.5*SIN(2.*BETA))**(2./3.))
C
C                                      Mass Transfer Analogy
C                                      (Fan/Tsuchiya, Ch 9)
           CALL DIFFUSEC(CFTYPE,DFTYPE,TC(I),P(I),ZD)
           if(iflagon.eq.1)print*,'Fan/Tsuchiya'
           EC=2.
           IF(BETA.LT.(PI/2.)) THEN
               BH=2.*R(I)*SIN(BETA)/EC
           ELSE
               BH=2.*R(I)/EC
           ENDIF
           DE=BH*EC**.6667
           ZPE=DE*UD(I)/ZD
           SH=1.79*(3.*EC**2+4.)**.6667/(EC**2+4.)*PEC(I)**.5
           SC=VISD/DENSD(I)/ZD
           SHNU=SH*(PR/SC)**(1./3.)
           HFT=SHNU*CKVD/(2*R(I))
           IF (XD(I).LT.1.0) THEN
               HH=(1-XD(i))*HTH+XD(i)*HFT
           ELSE
               DDNORM2=(I-IXDREF)*DZ/(2.*R(IXDREF))
               IF(DDNORM2.LE.10) THEN
                   HH=(.5*HBBR+.5*HFT*(1.-DDNORM2/10.)**2)
                   IF(HH.LT.HBBR) HH=HBBR
               ELSE
                   HH=HBBR
               ENDIF
           ENDIF
        ENDIF
        HSH=0.
        HHTS=0.
```

```
            HJAC=0.
            HCUL=0.
       ENDIF
       HS(I)=HSH
       HT(I)=HTH
       HCB(I)=HCBN
       HST(I)=HSTR
       HBB(I)=HBBR
       H(I)=HH
 9090  CONTINUE
C
C HEAT TRANSFER
C
       if(iflagon.eq.1)print*,'HTC-1'
       IF ((2*R(I)).LE.DZ) THEN
          SURFACE=4*PI*R(I)**2
       ELSE
          SURFACE=2*PI*R(I)*DZ
       ENDIF
       if(iflagon.eq.1)print*,'HTC-2'
       QDJ=HH*(TC(I)-TD(I))*SURFACE*NB
       QCV(I)=QDJ
       QCJ=-QDJ*ETA
       QCV2(I)=QCJ
C
       IF(I.EQ.N) GOTO 20
C
C CHECK FOR FLOODING CONDITION
C
       IF(IFLAGON.EQ.1)PRINT*,'Flood Check'
       IF((UC(I)*UDZ(I)).GE.0) THEN
          PRINT*,'***********************************************'
          PRINT*,'******** FLOODING HAS OCCURRED IN COLOMN ********'
          PRINT*,'***********************************************'
          PRINT*,'ITERATION: ',ICOUNT
          PRINT*,'LOCATION      ',I,'/',N,'    Z= ',I*DZ,' m'
          PRINT*,'DISPERSED FLUID FLOW RATE  = ',MRD,' kg/sec'
          PRINT*,'CONTINUOUS FLUID FLOW RATE = ',MRC,' kg/sec'
          PRINT*,'DISPERSED FLUID VELOCITY   = ',UDZ(I),' m/sec'
          PRINT*,'RELATIVE FLUID VELOCITY    = ',UD(I),' m/sec'
          PRINT*,'CONTINUOUS FLUID VELOCITY  = ',UC(I),' m/sec'
          PRINT*,'HOLDUP                     = ',HUR(I)
          GOTO 9999
       ENDIF
C
C CHECK FOR DISPERSED FLUID HOLDUP REVERSAL
C
       IF(IFLAGON.EQ.1)PRINT*,'Holdup Check'
       IF(HUR(I).GT.0.95) THEN
          PRINT*,'***********************************************'
          PRINT*,'******** HOLDUP RATIO HAS EXCEEDED 0.95 ********'
          PRINT*,'***********************************************'
          PRINT*,'ITERATION: ',ICOUNT
          PRINT*,'LOCATION      ',I,'/',N,'    Z= ',I*DZ/N,' m'
          PRINT*
          PRINT*,' DISPERSED FLUID FLOW RATE = ',MRD,' kg/sec'
          PRINT*,'CONTINUOUS FLUID FLOW RATE = ',MRC,' kg/sec'
          PRINT*
          PRINT*,' DISPERSED FLUID HOLDUP    = ',HUR(I)
          PRINT*
          GOTO 9999
       ENDIF
```

```
C
            DENSDJ=DENSD(I)
            DENSCJ=DENSC(I)
C
C   RUNGE-KUTTA SOLUTION
C     4th order
c
            IF(IFLAGON.EQ.1)PRINT*,'Runge-Kutta'
            DO 10 J=1,4
            IF(IFLAGON.EQ.1)PRINT*,'RK-K values'
                KP(J)=dz*(-MRD/DXAREA*UDPR-MRC/DXAREA*UCPR
      #              -(DENSCJ*(1-PHI)+DENSDJ*PHI)*G)
                KHD(J)=dz*(QDJ/DZ/MRD)
                KHC(J)=dz*(QCJ/DZ/MRC)
C
            IF(J.EQ.1.OR.J.EQ.2) THEN
                PPI=P(I)+.5*KP(J)/1000.
                HDI=HD(I)+.5*KHD(J)/1000.
                HCI=HC(I)+.5*KHC(J)/1000.
            ELSEIF(J.EQ.3.) THEN
                PPI=P(I)+KP(J)/1000.
                HDI=HD(I)+KHD(J)/1000.
                HCI=HC(I)+KHC(J)/1000.
            ELSEIF(J.GT.3) THEN
                GOTO 10
            ENDIF
C
            IF(IFLAGON.EQ.1)PRINT*,'RK-Dispersed density'
                IF(DFCAT.EQ.1) THEN
                    PGIVEN=PPI
                    HGIVEN=HDI
                    CALL SIFLUID ('PH',DFTYPE,PGIVEN,HGIVEN,XDI,SDI,HDI,
      #                  VDI,UDI,TDI,PDI,SDLI,HDLI,VDLI,UDLI,SDVI,
      #                  HDVI,VDVI,UDVI)
                    CALL QUALCHCK(XDI)
                    DENSDJ=1./VDI
                    IF(VDLI*VDVI.NE.0) THEN
                        RHODL=1./VDLI
                        RHODV=1./VDVI
                    ENDIF
                ELSEIF(DFCAT.EQ.2) THEN
                    CALL FLTHCAP(DFTYPE,TD(I),P(I),CPDI,RHOD1,XDI,ITRNG)
                    CALL TRNGCHK(ITRNG,td(i))
                    TDI=TD(I)+(HDI-HD(I))/CPDI
                    CALL FLTHCAP(DFTYPE,TDI,P(I),CPD1,DENSDJ,XDI,ITRNG)
                    CALL TRNGCHK(ITRNG,tdi)
                ENDIF
            IF(IFLAGON.EQ.1)PRINT*,'RK-Continuous density'
                IF(CFCAT.EQ.1) THEN
                    PGIVEN=PPI
                    HGIVEN=HCI
                    CALL SIFLUID ('PH',CFTYPE,PGIVEN,HGIVEN,XCI,SCI,HCI,
      #                  VCI,UCI,TCI,PCI,SCLI,HCLI,VCLI,UCLI,SCVI,
      #                  HCVI,VCVI,UCVI)
                    CALL QUALCHCK(XCI)
                    DENSCJ=1./VCI
                ELSEIF(CFCAT.EQ.2) THEN
                    CALL FLTHCAP(CFTYPE,TC(I),P(I),CPCI,RHOC1,XC1,ITRNG)
                    CALL TRNGCHK(ITRNG,tc(i))
                    TCI=TC(I)+(HCI-HC(I))/CPCI
                    CALL FLTHCAP(CFTYPE,TCI,P(I),CPC1,DENSCJ,XC1,ITRNG)
                    CALL TRNGCHK(ITRNG,tci)
```

```
            ENDIF
            IF(IFLAGON.EQ.1)PRINT*,'RK-Dispersed Properties'
            TGIVEN=TDI
            PGIVEN=PPI*1000.
            CALL PROPTY(DFTYPE,TGIVEN,PGIVEN,CKLD,CKVD,VISLD,VISVD,
     #          SIGD,ITRNG)
            CALL TRNGCHK(ITRNG,tgiven)
            IF(IFLAGON.EQ.1)PRINT*,'RK-Continuous Properties'
            TGIVEN=TCI
            PGIVEN=PPI*1000.
            CALL PROPTY(CFTYPE,TGIVEN,PGIVEN,CKC(0),CKC(1),
     #          VISC(0),VISC(1),SIGC,ITRNG)
            CALL TRNGCHK(ITRNG,tgiven)
            ALPHAC=CKC(IX)/DENSCJ/CPC
C
C BETA
C
            IF(IFLAGON.EQ.1)PRINT*,'RK-Beta'
            IF(XDI.GT.0.0.AND.XDI.LT.1.0) THEN
                CALL BBLMIX(RHODL,RHODV,XDI,BETA)
            ELSEIF(XDI.LE.0.0) THEN
                BETA=0.0
            ELSEIF(XDI.GE.1.0) THEN
                BETA=PI
            ENDIF
            IF(BETA.GT.PI) BETA=PI
C
C BUBBLE RADIUS
C
            IF(IFLAGON.EQ.1)PRINT*,'RK-radius'
            RJ=R(IREF)*(DENSD(IREF)/DENSDJ)**(1./3.)
            IF(WG(I).NE.0.) THEN
                VOLBUB=4./3.*PI*RJ**3+WG(I)*MB/DENSCG
                RJ=(VOLBUB*3./4./PI)**(1./3.)
            ENDIF
C
            IF(I.EQ.0.OR.I.EQ.IREF) THEN
                RECJ=DFNSC(I)*2.*RJ*ABS(UD(I))/VISC(IX)
            ELSE
                RECJ=DENSC(I)*2.*RJ*ABS(UD(I-1))/VISC(IX)
            ENDIF
C
c     Tochitani et al. Coefficient
            IF(IFLAGON.EQ.1)PRINT*,'RK-Tochitani'
            HTJ=CKC(IX)/2/RJ*(ABS(UD(I))*2*RJ/ALPHAC)**(1./3.)
     #          *(0.466194077*(PI-BETA+.5*SIN(2.*BETA))**(2./3.))
            IF(XDI.LE.0.0) THEN
c     Sideman Coefficient
               IF(IFLAGON.EQ.1)PRINT*,'RK-Sideman'
               HSJ=.00375*ABS(UD(I))*2*RJ/ALPHAC*(1./(1.+VISC(IX)/
     #             VISLD))*CKLD/2./RJ
c     Sideman/Tochitani series combination
               HHTSJ=HTJ*HSJ/(HTJ+HSJ)
c     Jacobs (Sideman) High Circulation with Decay
               IF(IFLAGON.EQ.1)PRINT*,'RK-Jacobs(Sideman)'
C              HJACJ=50.+.0085*RECJ*PRANDTLD**.7*CKC(IX)/2./RJ
               VKV=1.-1.45*(2.+3.*VISD/VISC(IX))/(1.+(DENSDJ*VISD/
     #             DENSCJ/VISC(IX))**.5)*RECJ**(-.5)
               HJACJ=(2.+1.13*(PEC(I)*VKV)**.5)*CKC(IX)/2./RJ
               HJTJ=HTJ*HJACJ/(HTJ+HJACJ)
               DDNORM=(I-IREF)*DZ/(2.*R(IREF))
               IF(DDNORM.LE.30) THEN
```

```
                         HHJ=HJTJ*(1.-DDNORM/30.)**2
   C                       HHJ=(0.0*HHTSJ+1.0*HJACJ*(1.-DDNORM/10.)**2)
                           IF(HHJ.LT.HHTSJ) HHJ=HHTSJ
                         ELSE
                           HHJ=HHTSJ
                         ENDIF
                         HCBNJ=0.
                         HBBRJ=0.
                       ELSE
   C     Coban Modification
                         HCBNJ=5.*CKVD/RJ*(1.-0.466194077*(PI-BETA
   #                         +.5*SIN(2.*BETA))**(2./3.))
   C     Brickman/Boehm Modification
   C     Steinberger & Treybal Coefficient
                         IF(IFLAGON.EQ.1)PRINT*,'RK-Brickman/Boehm'
                         CALL H2OBETA(TC(I),CBeta)
                         GR=9.81*CBeta*ABS(TD(I)-TC(I))*(2*RJ)**3/(VISC(IX)/
   #                         DENSCJ)
                         NUO=2.+.569*(GR*PR)**.25
                         NUC=NUO+.347*RECJ**.62*PR**.31
                         HSTRJ=NUC*CKC(IX)/2./RJ
                         HBBRJ=5.*HSTRJ*CKVD/(5.*CKVD+R(I)*HSTRJ)*
   #                         (1.-0.466194077*(PI-BETA+.5*SIN(2.*BETA))**(2./3.))
   C
   C     Transfer analogy (Fan/Tsuchiya, Ch 9)
   C
                         CALL DIFFUSEC(CFTYPE,DFTYPE,TC(I),P(I),ZD)
                         IF(IFLAGON.EQ.1)PRINT*,'RK-Fan/Tsuchiya'
                         EC=2.
                         IF(BETA.LT.(PI/2.)) THEN
                           BH=2.*R(I)*SIN(BETA)/EC
                         ELSE
                           BH=2.*R(I)/EC
                         ENDIF
                         DE=BH*EC**.6667
                         ZPE=DE*UD(I)/ZD
                         SH=1.79*(3.*EC**2+4.)**.6667/(EC**2+4.)
   #                         *PEC(I)**.5
                         SCJ=VISD/DENSDJ/ZD
                         SHNU=SH*(PR/SCJ)**(1./3.)
                         HFT=SHNU*CKVD/(2*R(I))
                         HFT=SH*Ckvd/(2*R(I))
                         IF (XD(I).LT.1.0) THEN
                           HHJ=(1-XD(i))*HTJ+XD(i)*HFT
                         ELSE
                           IF(DDNORM2.LE.10) THEN
                             HHJ=(.5*HBBRJ+.5*HFT*(1.-DDNORM2/10.)**2)
                             IF(HHJ.LT.HBBRJ) HHJ=HBBRJ
                           ELSE
                             HHJ=HBBRJ
                           ENDIF
                         ENDIF
                         HSJ=0.
                         HHTSJ=0.
                         HJACJ=0.
                         HCULJ=0.
                       ENDIF
                       IF(IFLAGON.EQ.1)PRINT*,'RK-HTC-1'
                       IF((2*RJ).LE.DZ) THEN
                         SURFJ=4*PI*RJ**2
                       ELSE
                         SURFJ=2*PI*RJ*DZ
```

```
                ENDIF
                QDJ=HHJ*(TCI-TDI)*SURFJ*NB
                QCJ=-QDJ*eta
C
                IF(IFLAGON.EQ.1)PRINT*,'Completed J=',j
    10          CONTINUE
                IF(IFLAGON.EQ.1)PRINT*,'End Runge-Kutta loop'
C

                KPC=(KP(1)+2*KP(2)+2*KP(3)+KP(4))/6.
                KHDC=(KHD(1)+2*KHD(2)+2*KHD(3)+KHD(4))/6.
                KHCC=(KHC(1)+2*KHC(2)+2*KHC(3)+KHC(4))/6.

C

                P(I+1)=P(I)+KPC/1000.
                HD(I+1)=HD(I)+KHDC/1000.
                HC(I+1)=HC(I)+ETA*KHCC/1000.
C

                IF(DFCAT.EQ.1) THEN
                   PGIVEN=P(I+1)
                   HGIVEN=HD(I+1)
                   CALL SIFLUID('PH',DFTYPE,PGIVEN,HGIVEN,XD(I+1),SD,
    #                   HD(I+1),VD,UID,TD(I+1),PD,SDL,HDL,VDL,UDL,SDV,
    #                   HDV,VDV,UDV)
                   CALL QUALCHCK(XD(I+1))
                   DENSD(I+1)=1./VD
                   IF(VDL*VDV.NE.0) THEN
                      RHODL=1./VDL
                      RHODV=1./VDV
                   ENDIF
                ELSEIF(DFCAT.EQ.2) THEN
                   CALL FLTHCAP(DFTYPE,TD(I),P(I+1),CPD,DENSD(I+1),XD(I+1),
    #                   ITRNG)
                   CALL TRNGCHK(ITRNG,td(i))
                   TD(I+1)=TD(I)+(HD(I+1)-HD(I))*1000./CPD
                   CALL FLTHCAP(DFTYPE,TD(I+1),P(I+1),CPD,DENSD(I+1),
    #                   XD(I+1),ITRNG)
                   CALL TRNGCHK(ITRNG,td(i+1))
                ENDIF
C

                IF(CFCAT.EQ.1) THEN
                   PGIVEN=P(I+1)
                   HGIVEN=HC(I+1)
                   CALL SIFLUID('PH',CFTYPE,PGIVEN,HGIVEN,XC(I+1),SC,HC(I+1)
    #                   ,VC,UIC,TC(I+1),PC,SCL,HCL,VCL,UCL,SCV,HCV,VCV,UCV)
                   CALL QUALCHCK(XC(I+1))
                   DENSC(I+1)=1./VC
                ELSEIF(CFCAT.EQ.2) THEN
                   CALL FLTHCAP(CFTYPE,TC(I),P(I+1),CPC,DENSC(I+1),XC(I+1),
    #                   ITRNG)
                   CALL TRNGCHK(ITRNG,tc(i))
                   TC(I+1)=TC(I)+(HC(I+1)-HC(I))*1000./CPC
                   CALL FLTHCAP(CFTYPE,TC(I+1),P(I+1),CPC,DENSC(I+1),XC(I+1),
    #                   ITRNG)
                   CALL TRNGCHK(ITRNG,tc(i+1))
                ENDIF
                IF(XC(I+1).NE.CQUAL) THEN
                   WRITE(7,*)'CONTINUOUS FLUID QUALITY CHANGE OF STATE'
                   WRITE(7,*)' CONT FLUID QUALITY= ',XC(I+1)
                   WRITE(7,*)'TOO MUCH HEAT MAY BE TRANSFERING'
                ENDIF
C
C
```

```
                IF(IAF.EQ.1) ACCELF=ICOUNT
                IF(TCNFIG.EQ.1) THEN
                   IF(ICNFIG.EQ.1) THEN
                      IF(TC(I+1).GT.TEMPC) THEN
                         IF(ICOUNT.GT.2) TUPPER=TC(0)+(TUPPER-TC(0))/ACCELF
                         ITLIM=1
                         GOTO 11
                      ENDIF
                   ELSE
                      IF(TD(I+1).LT.TEMPD) THEN
                         IF(ICOUNT.GT.2) TLOWER=TD(0)-(TD(0)-TLOWER)/ACCELF
                         ITLIM=1
                         GOTO 11
                      ENDIF
                   ENDIF
                ELSE
                   IF(ICNFIG.EQ.1) THEN
                      IF(TC(I+1).LT.TEMPC) THEN
                         IF(ICOUNT.GT.2) TLOWER=TC(0)-(TC(0)-TLOWER)/ACCELF
                         ITLIM=1
                         GOTO 11
                      ENDIF
                   ELSE
                      IF(TD(I+1).GT.TEMPD) THEN
                         IF(ICOUNT.GT.2) TUPPER=TD(0)+(TUPPER-TD(0))/ACCELF
                         ITLIM=1
                         GOTO 11
                      ENDIF
                   ENDIF
                ENDIF
       C
       20       CONTINUE
                ITLIM=0
                richard=1.0
       C
       C        END DIFFERENTIAL EQUATION SOLUTION RUN
       C
                IF(IFLAGON.EQ.1)PRINT*,'END MARCHING:TESTING FOR CONVERGENCE'
       C        TEST FOR CORRECT BOUNDARY CONDITION STARTING TEMPERATURE
       C
                IF(ICNFIG.EQ.1) THEN
                   IF (CFCAT.EQ.1) THEN
                      IF(ABS(HC(N)-HCZ).LE.HTOL) THEN
                         CALL PRNTRSLT(ICOUNT,IPASS)
                         GOTO 9999
                      ENDIF
                   ELSEIF(CFCAT.EQ.2) THEN
                      IF(ABS(TC(N)-TEMPC).LE.TTOL) THEN
                         CALL PRNTRSLT(ICOUNT,IPASS)
                         GOTO 9999
                      ENDIF
                   ENDIF
                ELSE
                   IF(DFCAT.EQ.1) THEN
                      IF(ABS(HD(N)-HDZ).LE.HTOL) THEN
                         CALL PRNTRSLT(ICOUNT,IPASS)
                         GOTO 9999
                      ENDIF
                   ELSEIF(DFCAT.EQ.2) THEN
                      IF(ABS(TD(N)-TEMPD).LE.TTOL) THEN
                         CALL PRNTRSLT(ICOUNT,IPASS)
                         GOTO 9999
```

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                ENDIF
              ENDIF
            ENDIF
C
            IF(TUPPER-TLOWER.LE.TTOL) THEN
              CALL PRNTRSLT(ICOUNT,IPASS)
              GOTO 9999
            ENDIF
C
C   ADJUST STARTING TEMPERATURE GUESS
            IF(IFLAGON.EQ.1)PRINT*,'ADJUSTING TEMPERATURE GUESS'
C
 9997       IF(IAF.EQ.1) ACCELF=ICOUNT
            IF(ICNFIG.EQ.1) THEN
              IF(HC(N).GT.HCZ) THEN
                IF(ICOUNT.GT.3) TUPPER=TC(0)+(TUPPER-TC(0))/ACCELF
              ELSE
                IF(ICOUNT.GT.3) TLOWER=TC(0)-(TC(0)-TLOWER)/ACCELF
              ENDIF
            ELSE
              IF(HD(N).GT.HDZ) THEN
                IF(ICOUNT.GT.3) TUPPER=TD(0)+(TUPPER-TD(0))/ACCELF
              ELSE
                IF(ICOUNT.GT.3) TLOWER=TD(0)-(TD(0)-TLOWER)/ACCELF
              ENDIF
            ENDIF
            GOTO 11
C
C
 9999       IF(IPASS.NE.1) GOTO 9998
C
C       LOCATION OF FUTURE 2nd PASS ITERATION WITH IMPROVED INITIAL
C       GUESSES
C
 9998       STOP
            END
C_____
            SUBROUTINE FLUIDCAT(FTYPE,FCAT,R)
            CHARACTER*6 FTYPE
            FCAT=3
            R=0.0
C
            IF(FTYPE.EQ.'H2O    ') THEN
              FCAT=1
              R=461.48
            ELSEIF(FTYPE.EQ.'PENT   ') THEN
              FCAT=1
              R=115.24
            ELSEIF(FTYPE.EQ.'BUT    ') THEN
              FCAT=1
              R=143.05
            ELSEIF(FTYPE.EQ.'ISOB   ') THEN
              FCAT=1
              R=143.05
            ELSEIF(FTYPE.EQ.'ISOP   ') THEN
              FCAT=1
              R=115.24
            ELSEIF(FTYPE.EQ.'HEP    ') THEN
              FCAT=1
            ELSEIF(FTYPE.EQ.'ETHYL  ') THEN
              FCAT=1
            ELSEIF(FTYPE.EQ.'METH   ') THEN
```

```
        FCAT=1
      ELSEIF(FTYPE.EQ.'F11    ') THEN
        FCAT=1
      ELSEIF(FTYPE.EQ.'F12    ') THEN
        FCAT=1
      ELSEIF(FTYPE.EQ.'F13    ') THEN
        FCAT=1
      ELSEIF(FTYPE.EQ.'F22    ') THEN
        FCAT=1
      ELSEIF(FTYPE.EQ.'F23    ') THEN
        FCAT=1
      ELSEIF(FTYPE.EQ.'F113   ') THEN
        FCAT=1
      ELSEIF(FTYPE.EQ.'F114   ') THEN
        FCAT=1
      ELSEIF(FTYPE.EQ.'TH44   ') THEN
        FCAT=2
      ELSEIF(FTYPE.EQ.'TH55   ') THEN
        FCAT=2
      ELSEIF(FTYPE.EQ.'TH60   ') THEN
        FCAT=2
      ELSEIF(FTYPE.EQ.'TH66   ') THEN
        FCAT=2
      ELSEIF(FTYPE.EQ.'TH88   ') THEN
        FCAT=2
      ELSEIF(FTYPE.EQ.'CFAF   ') THEN
        FCAT=2
      ELSEIF(FTYPE.EQ.'CFFG   ') THEN
        FCAT=2
      ELSEIF(FTYPE.EQ.'CFHTF  ') THEN
        FCAT=2
      ELSEIF(FTYPE.EQ.'SYLTH8 ') THEN
        FCAT=2
      ELSEIF(FTYPE.EQ.'THM550 ') THEN
        FCAT=2
      ELSEIF(FTYPE.EQ.'THM600 ') THEN
        FCAT=2
      ELSEIF(FTYPE.EQ.'THM800 ') THEN
        FCAT=2
      ELSEIF(FTYPE.EQ.'DTSR1  ') THEN
        FCAT=2
      ELSEIF(FTYPE.EQ.'DT4000 ') THEN
        FCAT=2
      ELSEIF(FTYPE.EQ.'DT4030 ') THEN
        FCAT=2
      ELSEIF(FTYPE.EQ.'DT4040 ') THEN
        FCAT=2
      ELSEIF(FTYPE.EQ.'DT4050 ') THEN
        FCAT=2
      ELSEIF(FTYPE.EQ.'DT4060 ') THEN
        FCAT=2
      ELSEIF(FTYPE.EQ.'DFHD30 ') THEN
        FCAT=2
      ELSEIF(FTYPE.EQ.'DFHD40 ') THEN
        FCAT=2
      ELSEIF(FTYPE.EQ.'DFHD50 ') THEN
        FCAT=2
      ELSEIF(FTYPE.EQ.'DFHD60 ') THEN
        FCAT=2
      ELSEIF(FTYPE.EQ.'DWFHD  ') THEN
        FCAT=2
      ELSEIF(FTYPE.EQ.'DWFRST ') THEN
```

```
      FCAT=2
      ELSEIF(FTYPE.EQ.'PARANF') THEN
      FCAT=2
      ELSEIF(FTYPE.EQ.'PARAHE') THEN
      FCAT=2
      ELSEIF(FTYPE.EQ.'MTHVP1') THEN
      FCAT=2
      ELSEIF(FTYPE.EQ.'THRMX ') THEN
      FCAT=2
      ELSEIF(FTYPE.EQ.'AIR   ') THEN
      FCAT=2
      R=287.03
      ELSEIF(FTYPE.EQ.'CO2   ') THEN
      FCAT=2
      R=188.91
      ELSEIF(FTYPE.EQ.'H2    ') THEN
      FCAT=2
      ELSEIF(FTYPE.EQ.'N2    ') THEN
      FCAT=2
      ELSEIF(FTYPE.EQ.'O2    ') THEN
      FCAT=2
      ELSEIF(FTYPE.EQ.'NH3   ') THEN
      FCAT=2
      ELSEIF(FTYPE.EQ.'MS20  ') THEN
      FCAT=2
      ELSEIF(FTYPE.EQ.'TRAN  ') THEN
      FCAT=2
      ELSEIF(FTYPE.EQ.'TM1   ') THEN
      FCAT=2
      ELSEIF(FTYPE.EQ.'VM4   ') THEN
      FCAT=2
      ELSEIF(FTYPE.EQ.'KHF22 ') THEN
      FCAT=2
      ELSEIF(FTYPE.EQ.'ENG   ') THEN
      FCAT=2
      ELSEIF(FTYPE.EQ.'ETHYLG') THEN
      FCAT=2
      ELSEIF(FTYPE.EQ.'GLYCRN') THEN
      FCAT=2
      ELSEIF(FTYPE.EQ.'HG    ') THEN
      FCAT=2
      ENDIF
C
100   RETURN
      END
C_____
      SUBROUTINE DIFFUSEC(CFTYPE,DFTYPE,TC,P,D)
      REAL KTE(81),OMEGA(81)
      REAL KTE12,OMEGA12,M1,M2
      CHARACTER*6,CFTYPE
      CHARACTER*6,DFTYPE
      DATA(KTE(I),I=1,81)/.3,.35,.4,.45,.5,.55,.6,.65,.7,.75,.8,.85,.9,
     #.95,1.,1.05,1.1,1.15,1.2,1.25,1.3,1.35,1.4,1.45,1.5,1.55,1.6,
     #1.65,1.7,1.75,1.8,1.85,1.9,1.95,2.,2.1,2.2,2.3,2.4,2.5,2.6,2.7,
     #2.8,2.9,3.,3.1,3.2,3.3,3.4,3.5,3.6,3.7,3.8,3.9,4.,4.1,4.2,4.3,
     #4.4,4.5,4.6,4.7,4.8,4.9,5.,6.,7.,8.,9.,10.,20.,30.,40.,50.,60.,
     #70.,80.,90.,100.,200.,300./
      DATA(OMEGA(I),I=1,81)/2.662,2.476,2.318,2.184,2.066,1.966,1.877,
     #1.798,1.729,1.667,1.612,1.562,1.517,1.476,1.439,1.406,1.375,
     #1.346,1.32,1.296,1.273,1.253,1.233,1.215,1.198,1.182,1.167,1.153,
     #1.14,1.128,1.116,1.105,1.094,1.084,1.075,1.057,1.041,1.026,1.012,
     #.9996,.9878,.977,.9672,.9576,.949,.9406,.9328,.9256,.9186,.912,
```

```fortran
#.9058,.8998,.8942,.8888,.8836,.8788,.874,.8694,.8652,.861,.8568,
#.853,.8492,.8456,.8422,.8124,.7896,.7712,.7556,.7424,.664,.6232,
#.596,.5756,.5596,.5464,.5352,.5256,.513,.4644,.436/
D=0.0
IF(CFTYPE.EQ.'ARGON ') THEN
      SIG1=3.542
      EK1=93.3
      M1=39.948
ELSEIF(CFTYPE.EQ.'HEL    ') THEN
      SIG1=2.551
      EK1=10.22
      M1=4.0026
ELSEIF(CFTYPE.EQ.'KRYP  ') THEN
      SIG1=3.655
      EK1=178.9
      M1=83.8
ELSEIF(CFTYPE.EQ.'AIR    ') THEN
      SIG1=3.711
      EK1=78.6
      M1=29.0
ELSEIF(CFTYPE.EQ.'METH  ') THEN
      SIG1=3.758
      EK1=148.6
      M1=16.0426
ELSEIF(CFTYPE.EQ.'CO2   ') THEN
      SIG1=3.941
      EK1=195.2
      M1=44.0098
ELSEIF(CFTYPE.EQ.'ETHYL ') THEN
      SIG1=4.163
      EK1=224.7
      M1=28.0536
ELSEIF(CFTYPE.EQ.'ETH    ') THEN
      SIG1=4.443
      EK1=215.7
      M1=30.0694
ELSEIF(CFTYPE.EQ.'PROPYL') THEN
      SIG1=4.678
      EK1=298.9
      M1=41.0725
ELSEIF(CFTYPE.EQ.'BUT    ') THEN
      SIG1=4.687
      EK1=531.4
      M1=58.123
ELSEIF(CFTYPE.EQ.'ISOB  ') THEN
      SIG1=5.278
      EK1=330.1
      M1=58.123
ELSEIF(CFTYPE.EQ.'PENT  ') THEN
      SIG1=5.784
      EK1=341.1
      M1=72.1498
ELSEIF(CFTYPE.EQ.'HEX    ') THEN
      SIG1=5.949
      EK1=399.3
      M1=86.1766
ELSEIF(CFTYPE.EQ.'H2     ') THEN
      SIG1=2.827
      EK1=59.7
      M1=2.0158
ELSEIF(CFTYPE.EQ.'H2O   ') THEN
      SIG1=2.641
```

```
        EK1=809.1
        M1=18.0152
ELSEIF(CFTYPE.EQ.'N2     ') THEN
        SIG1=3.798
        EK1=71.4
        M1=28.0134
ELSEIF(CFTYPE.EQ.'O2     ') THEN
        SIG1=3.467
        EK1=106.7
        M1=31.9988
ELSEIF(CFTYPE.EQ.'H2S    ') THEN
        SIG1=3.623
        EK1=301.1
        M1=34.0818
ENDIF
C
C

IF(DFTYPE.EQ.'ARGON  ') THEN
        SIG2=3.542
        EK2=93.3
        M2=39.948
ELSEIF(DFTYPE.EQ.'HEL    ') THEN
        SIG2=2.551
        EK2=10.22
        M2=4.0026
ELSEIF(DFTYPE.EQ.'KRYP   ') THEN
        SIG2=3.655
        EK2=178.9
        M2=83.8
ELSEIF(DFTYPE.EQ.'AIR    ') THEN
        SIG2=3.711
        EK2=78.6
        M2=29.0
ELSEIF(DFTYPE.EQ.'METH   ') THEN
        SIG2=3.758
        EK2=148.6
        M2=16.0426
ELSEIF(DFTYPE.EQ.'CO2    ') THEN
        SIG2=3.941
        EK2=195.2
        M2=44.0098
ELSEIF(DFTYPE.EQ.'ETHYL ') THEN
        SIG2=4.163
        EK2=224.7
        M2=28.0536
ELSEIF(DFTYPE.EQ.'ETH    ') THEN
        SIG2=4.443
        EK2=215.7
        M2=30.0694
ELSEIF(DFTYPE.EQ.'PROPYL') THEN
        SIG2=4.678
        EK2=298.9
        M2=41.0725
ELSEIF(DFTYPE.EQ.'BUT    ') THEN
        SIG2=4.687
        EK2=531.4
        M2=58.123
ELSEIF(DFTYPE.EQ.'ISOB   ') THEN
        SIG2=5.278
        EK2=330.1
        M2=58.123
ELSEIF(DFTYPE.EQ.'PENT   ') THEN
```

```fortran
        SIG2=5.784
        EK2=341.1
        M2=72.1498
      ELSEIF(DFTYPE.EQ.'HEX     ') THEN
        SIG2=5.949
        EK2=399.3
        M2=86.1766
      ELSEIF(DFTYPE.EQ.'H2      ') THEN
        SIG2=2.827
        EK2=59.7
        M2=2.0158
      ELSEIF(DFTYPE.EQ.'H2O     ') THEN
        SIG2=2.641
        EK2=809.1
        M2=18.0152
      ELSEIF(DFTYPE.EQ.'N2      ') THEN
        SIG2=3.798
        EK2=71.4
        M2=28.0134
      ELSEIF(DFTYPE.EQ.'O2      ') THEN
        SIG2=3.467
        EK2=106.7
        M2=31.9988
      ELSEIF(DFTYPE.EQ.'H2S     ') THEN
        SIG2=3.623
        EK2=301.1
        M2=34.0818
      ENDIF
C
      IF((EK1*EK2).LE.0.0) GOTO 100
      IF((SIG1*SIG2).EQ.0.0) GOTO 100
      TK=TC+273.15
      SIG12=.5*(SIG1+SIG2)
      KTE12=1./(SQRT(EK1*EK2)/TK)
      DO 10 I=80,1,-1
        IF(KTE(I).LE.KTE12) THEN
          OMEGA12=(KTE12-KTE(I))/(KTE(I+1)-KTE(I))*
     #           (OMEGA(I+1)-OMEGA(I))+OMEGA(I)
          GOTO 20
        ENDIF
10    CONTINUE
      GOTO 100
C
C     CHAPMAN-ENSKOG THEORY FOR DIFFUSION COEFFICIENT
C
20    D=1.86E-03*TK**1.5*(1./M1+1./M2)/(P/101.325)/SIG12**2/OMEGA12
      D=D/10000.
C
100   RETURN
      END
C_____
      SUBROUTINE PPRNT
      REAL  UD(0:2001),UC(0:2001),TD(0:2001),TC(0:2001),
     #      HUR(0:2001),DENSD(0:2001),DENSC(0:2001),HD(0:2001),
     #      HC(0:2001),R(0:2001),QCV(0:2001),XD(0:2001),P(0:2001),
     #      XC(0:2001),CKC(0:1),VISC(0:1),BET(0:2001),H(0:2001),
     #      HS(0:2001),HT(0:2001),ALPHC(0:2001),VISCD(0:2001),
     #      RYNLD(0:2001),COEFD(0:2001),PEC(0:2001),HCB(0:2001),
     #      CPPC(0:2001),CPPD(0:2001),CKKC(0:2001),CKKD(0:2001),
     #      WG(0:2001),HM(0:2001),DIFF(0:2001),ALPHD(0:2001),
     #      VISCC(0:2001),QCV2(0:2001),HSTAG(0:2001),BPOP(0:2001),
     #      HBB(0:2001),HST(0:2001),UDZ(0:2001)
```

```
      COMMON/HHH/H,HS,HT,HCB,HBB,HST
      COMMON/ARRY/UDZ,UD,UC,TD,TC,P,HUR,DENSD,DENSC,HD,HC,R,QCV,
     #    DZ,XD,BET,CPPC,CPPD,CKKD,CKKC,PEC,VISCD,VISC,RYNLD,
     #    BPOP,VISCC,COEFD,WG,HM,DIFF,QCV2,HSTAG
      COMMON/SCLR/MRD,MRC,TEMPD,TEMPC,RO,PRESS,CQUAL,ICNFIG,TCNFIG,
     #    N,DNZAREA,DXVOLUME,DXLENGTH,DXRADIUS,DFTYPE,CFTYPE
      REAL MRD,MRC
      INTEGER TCNFIG
      CHARACTER*6,DFTYPE
      CHARACTER*6,CFTYPE
      WRITE(7,*)' '
      WRITE(7,*)'Input Values'
      WRITE(7,7001) DXLENGTH,DXRADIUS,PRESS
 7001 FORMAT(/,'       Heat Exchanger Length:   ',F7.2,' meters',/,
     #    '       Heat Exchanger Radius:   ',F7.2,' meters',/,
     #    'Nominal Operating Pressure:   ',F7.2,' kPa')
      WRITE(7,7002)DFTYPE,CFTYPE,MRD,MRC,TEMPD,TEMPC
 7002 FORMAT(/,18X,'Dispersed Fluid',5X,'Continuous Fluid',/,
     #    '              Fluid:',7X,A6,15X,A6,/,
     #    'Mass Flow Rate:',5X,F8.4,13x,F8.4,'    kg/sec',/,
     #    '     Inlet Temp:',3X,F8.2,13x,F8.2,'      deg C')
      WRITE(7,7003)RO,CQUAL
 7003 FORMAT(/,'Disp. Fld. Droplet/Bubble Radius:   ',F7.6,' meters',/,
     #    '         Continuous Fluid Quality:   ',F2.0,/)
      RETURN
      END
```

C_____

```
      SUBROUTINE PPRINT(ICOUNT,IPASS)
      REAL UD(0:2001),UC(0:2001),TD(0:2001),TC(0:2001),
     #    HUR(0:2001),DENSD(0:2001),DENSC(0:2001),HD(0:2001),
     #    HC(0:2001),R(0:2001),QCV(0:2001),XD(0:2001),P(0:2001),
     #    XC(0:2001),CKC(0:1),VISC(0:1),BET(0:2001),H(0:2001),
     #    HS(0:2001),HT(0:2001),ALPHC(0:2001),VISCD(0:2001),
     #    RYNLD(0:2001),COEFD(0:2001),PEC(0:2001),HCB(0:2001),
     #    CPPC(0:2001),CPPD(0:2001),CKKC(0:2001),CKKD(0:2001),
     #    WG(0:2001),HM(0:2001),DIFF(0:2001),ALPHD(0:2001),
     #    VISCC(0:2001),QCV2(0:2001),HSTAG(0:2001),BPOP(0:2001),
     #    HBB(0:2001),HST(0:2001),UDZ(0:2001)
      COMMON/HHH/H,HS,HT,HCB,HBB,HST
      COMMON/ARRY/UDZ,UD,UC,TD,TC,P,HUR,DENSD,DENSC,HD,HC,R,QCV,
     #    DZ,XD,BET,CPPC,CPPD,CKKD,CKKC,PEC,VISCD,VISC,RYNLD,
     #    BPOP,VISCC,COEFD,WG,HM,DIFF,QCV2,HSTAG
      COMMON/SCLR/MRD,MRC,TEMPD,TEMPC,RO,PRESS,CQUAL,ICNFIG,TCNFIG,
     #    N,DNZAREA,DXVOLUME,DXLENGTH,DXRADIUS,DFTYPE,CFTYPE
      COMMON/SCLR2/ETA
      REAL MRD,MRC,LMTD,MCPMIN
      INTEGER TCNFIG
      WRITE(7,*)'DCHX Parameter Profile'
      QXFRD=0.0
      QXFRC=0.0
      PRANDTLD=0.0
      PRANDTLC=0.0
      DO 10 I=0,N
         QXFRD=QXFRD+QCV(I)/ETA
         QXFRC=QXFRC+QCV2(I)
         PRANDTLD=PRANDTLD+CPPD(I)*VISCD(I)/CKKD(I)
         PRANDTLC=PRANDTLC+CPPC(I)*VISCC(I)/CKKC(I)
 10   CONTINUE
      PRANDTLD=PRANDTLD/N
      PRANDTLC=PRANDTLC/N
      LMTD=(ABS(TD(N)-TC(N))-ABS(TD(0)-TC(0)))/LOG(ABS(TD(N)-TC(N))/
```

```
#               ABS(TD(0)-TC(0)))
          UUVD=ABS(QXFRD)/DXVOLUME/LMTD
          UUVC=ABS(QXFRC)/DXVOLUME/LMTD
          IF(XD(0).NE.XD(N)) GOTO 20
          IF(ICNFIG.EQ.1) THEN
               CPPDS=CPPD(0)
               CPPCS=CPPC(N)
          ELSE
               CPPDS=CPPD(N)
               CPPCS=CPPC(0)
          ENDIF
          IF((ABS(MRD)*CPPDS).LT.(ABS(MRC)*CPPCS)) THEN
               MCPMIN=ABS(MRD)*CPPDS
          ELSE
               MCPMIN=ABS(MRC)*CPPCS
          ENDIF
          DTMAX=ABS(TEMPC-TEMPD)
          QIDEAL=MCPMIN*DTMAX
          eD=ABS(QXFRD)/QIDEAL
          eC=ABS(QXFRC)/QIDEAL
          DTDT=abs((TD(0)-TC(0))/(TD(N)-TC(N)))
          DUOC=(1.-LMTD/DTMAX)*(1.-ABS(LOG(DTDT))*(LMTD/DTMAX))
          WRITE(7,*)
          WRITE(7,7010)ICNFIG,TCNFIG,QXFRD,QXFRC,TD(0),TD(N),TC(0),
     #          TC(N),LMTD,DTDT,DUOC,UUVD,UUVC,eD,eC,qideal,
     #          PRANDTLD,PRANDTLC
          print*,qxfrd
          GOTO 30
20        WRITE(7,*)
          WRITE(7,7020)ICNFIG,TCNFIG,QXFRD,QXFRC,TD(0),
     #          TD(N),TC(0),TC(N),LMTD,DTDT,DUOC,UUVD,UUVC,
     #          PRANDTLD,PRANDTLC
          print*,qxfrd
7010      FORMAT(/,'  Fluid Flow Configuration:   ',I1,/,
     #              '  Temperature Configuration:  ',I1,//,
     #              'Total Device Heat Trans   D:  ',F10.0,'  Watts',/,
     #              'Total Device Heat Trans   C:  ',F10.0,'  Watts',//,
     #              'Dispersed Fluid Temp @ vz=0:  ',F6.1,'  deg C',/,
     #              'Dispersed Fluid Temp @ z=N:   ',F6.1,'  deg C',/,
     #              'Continuous Fluid Temp @z=0:   ',F6.1,'  deg C',/,
     #              'Continuous Fluid Temp @z=N:   ',F6.1,'  deg C',//,
     #              '  Log Mean Temp Difference:   ',F7.2, '    deg C',/,
     #              '                Parallelism:  ',f8.4,/,
     #              '  Optimal Fluid Usage Ind.:   ',f8.4,/,
     #              '  Volumetric Trans Coeff  D:  ',F12.4,'  W/m3 K',/,
     #              '  Volumetric Trans Coeff  C:  ',F12.4,'  W/m3 K',//,
     #              '      e-NTU Effectiveness D:  ',F8.3,/,
     #              '      e-NTU Effectiveness C:  ',F8.3,/,
     #              '      Max Ideal Transfer:    ',f10.0,//,
     #              '              Prandtl # (D):  ',f10.4,/,
     #              '              Prandtl # (C):  ',f10.4,/)
7020      FORMAT(/,'  Fluid Flow Configuration:   ',I1,/,
     #              '  Temperature Configuration:  ',I1,/,
     #              'Total Device Heat Trans   D:  ',F10.0,'  Watts',/,
     #              'Total Device Heat Trans   C:  ',F10.0,'  Watts',//,
     #              'Dispersed Fluid Temp @ z=0:   ',F6.1,'  deg C',/,
     #              'Dispersed Fluid Temp @ z=N:   ',F6.1,'  deg C',/,
     #              'Continuous Fluid Temp @z=0:   ',F6.1,'  deg C',/,
     #              'Continuous Fluid Temp @z=N:   ',F6.1,'  deg C',//,
     #              '  Log Mean Temp Difference:   ',F7.2,'    deg C',/,
     #              '                Parallelism:  ',f8.4,/,
     #              '  Optimal Fluid Usage Ind.:   ',f8.4,/,
```

```
#                  ' Volumetric Trans Coeff  D:   ',F12.4,' W/m3 K',/,
#                  ' Volumetric Trans Coeff  C:   ',F12.4,' W/m3 K',//,
#                  '          Prandtl # (D):   ',f10.4,/,
#                  '          Prandtl # (C):   ',f10.4,/)
7025     FORMAT('Adjusted Dispersed Fluid Nozzle Area: ',F6.3,//)
30       WRITE(7,7025)DNZAREA
         IF(QXFRD.GT.QXFRC)THEN
              WRITE(7,*)'HEAT TRANSFER IS FROM CONTINUOUS FLUID TO
DISPERSE
     #D FLUID'
         ELSE
              WRITE(7,*)'HEAT TRANSFER IS FROM DISPERSED FLUID TO
CONTINUOU
     #S FLUID'
         ENDIF
         WRITE(7,7011)ICOUNT
7011     FORMAT(//,'CONVERGENCE OCCURRED IN ',I3,' ITERATIONS')
         RETURN
         END
C_____
         SUBROUTINE PRNTRSLT(ICOUNT,IPASS)
         REAL  UD(0:2001),UC(0:2001),TD(0:2001),TC(0:2001),
     #         HUR(0:2001),DENSD(0:2001),DENSC(0:2001),HD(0:2001),
     #         HC(0:2001),R(0:2001),QCV(0:2001),XD(0:2001),p(0:2001),
     #         XC(0:2001),CKC(0:1),VISC(0:1),BET(0:2001),H(0:2001),
     #         HS(0:2001),HT(0:2001),ALPHC(0:2001),VISCD(0:2001),
     #         RYNLD(0:2001),COEFD(0:2001),PEC(0:2001),HCB(0:2001),
     #         CPPC(0:2001),CPPD(0:2001),CKKD(0:2001),CKKC(0:2001),
     #         WG(0:2001),HM(0:2001),DIFF(0:2001),VISCC(0:2001),
     #         QCV2(0:2001),HSTAG(0:2001),BPOP(0:2001),
     #         HBB(0:2001),HST(0:2001),UDZ(0:2001)
         REAL MRD,MRC,LMTD
         INTEGER TCNFIG
         COMMON/HHH/H,HS,HT,HCB,HBB,HST
         COMMON/ARRY/UDZ,UD,UC,TD,TC,P,HUR,DENSD,DENSC,HD,HC,R,QCV,
     #         DZ,XD,BET,CPPC,CPPD,CKKD,CKKC,PEC,VISCD,VISC,RYNLD,
     #         BPOP,VISCC,COEFD,WG,HM,DIFF,QCV2,HSTAG
         COMMON/SCLR/MRD,MRC,TEMPD,TEMPC,R0,PRESS,CQUAL,ICNFIG,TCNFIG,
     #         N,DNZAREA,DXVOLUME,DXLENGTH,DXRADIUS,DFTYPE,CFTYPE
         COMMON/SCLR2/ETA
         CHARACTER*6,CFTYPE
         CHARACTER*6,DFTYPE
         PRINT*,'PRINTING RESULTS'
         CALL PPRINT(ICOUNT,IPASS)
         WRITE(2,*)'DISPERSED FLUID RESULTS'
         WRITE(3,*)'CONTINUOUS FLUID RESULTS'
         WRITE(4,*)'FLUID AND HEAT TRANSFER VALUES'
         WRITE(5,*)'DISPERSED FLUID PARAMETERS'
         WRITE(6,*)'CONTINUOUS FLUID PARAMETERS'
         WRITE(9,*)'DISPERSED DROPLET/BUBBLE INFO'
         DO 1 I=2,6
1        WRITE(I,*)'DCHX Configuration = ',ICNFIG
         WRITE(2,*)'Dispersed Fluid:  ',DFTYPE
         WRITE(5,*)'Dispersed Fluid:  ',DFTYPE
         WRITE(3,*)'Continuous Fluid:  ',CFTYPE
         WRITE(6,*)'Continuous Fluid:  ',CFTYPE
         WRITE(9,*)'Dispersed Fluid:  ',DFTYPE
         WRITE(2,*)'Idx   Loc  Vel(a) Vel(r)  Temp Holdup HtXfer  Qual  D-
     #rad      Pop'
         WRITE(2,*)' i     z    Udz    Ud     Td   Phi   QcvD    Xd
     #r     nB'
         WRITE(2,*)'       m    m/s    m/s     C          W         -
```

```
      #m'
      WRITE(3,*)'Idx    Loc    Vel       Temp     HtXfer                    Press'
      WRITE(3,*)' i      z      Uc        Tc       QcvC      1-Phi           P'
      WRITE(3,*)'               m/s       C        W                         kPa'
      WRITE(4,*)'               Reynolds  Peclect  Drag              Ht Xfer'
      WRITE(4,*)'Idx    Loc    Number    Number   Coeff             Coeff   '
      WRITE(4,*)'        z      Re        Pe       Cd                h       '
      WRITE(4,*)'        m                                           W/m2 K  '
      WRITE(5,*)'                                           Thermal  Cond'
      WRITE(5,*)'Idx    Loc    Density   Viscosity          Capacit  Coeff
Ent
      #halpy'
      WRITE(5,*)' i      z      rho       mu                 Cp       k

      #Hd'
      WRITE(5,*)'        m      kg/m3     Pa-s              J/kg K   W/m K
J
      #/kg K'
      WRITE(6,*)'                                           Thermal  Cond'
      WRITE(6,*)'Idx    Loc    Density   Viscosity          Capacit  Coeff
Ent
      #halpy'
      WRITE(6,*)' i      z      rho       mu                 Cp       k

      #Hd'
      WRITE(6,*)'        m      kg/m3     Pa-s              J/kg K   W/m K
J
      #/kg K'
      WRITE(8,*)'Idx    Loc    Mass Rat  M Xfer Coeff'
      WRITE(8,*)' i      z      Wg        hM'
      WRITE(8,*)'        m                kg/sec m2'
      WRITE(9,*)' i      z      hT        hS       hTS       hST      hBB
      #      h'
C
      DO 10 I=N,0,-1
         Z=I*DZ
      WRITE(2,1002)I,Z,UDZ(I),UD(I),TD(I),HUR(I),QCV(I)/ETA,XD(I),R(I),
      #BPOP(I)
      WRITE(3,1003)I,Z,UC(I),TC(I),QCV2(I),1-HUR(I),P(I)
      WRITE(4,1004)I,Z,RYNLD(I),PEC(I),COEFD(I),H(I)
      WRITE(5,1005)I,Z,DENSD(I),VISCD(I),CPPD(I),CKKD(I),HD(I)
      WRITE(6,1006)I,Z,DENSC(I),VISCC(I),CPPC(I),CKKC(I),HC(I)
      WRITE(8,1008)I,Z,WG(I),HM(I)
      WRITE(9,1009)I,Z,hT(i),hS(i),hS(I)*hT(I)/(hS(I)+hT(I)),
      #      hST(I),hBB(I),H(I)
10    CONTINUE
1002  FORMAT(I4,1x,f6.3,2(1x,f6.3),1x,f6.1,1x,f5.3,1x,F6.0,1X,f6.4,
      #      1X,f6.5,1X,F7.0)
1003  FORMAT(I4,1x,f6.3,1x,f8.5,1x,f6.1,1x,f7.0,2x,f6.4,1x,f8.2)
1004  FORMAT(I4,1X,F6.3,2X,F7.0,2X,F8.0,2X,E9.3,2X,F7.1)
1005  FORMAT(I4,1X,F6.3,2X,F8.3,2X,E12.5,2X,F6.1,2X,F7.5,2X,F7.1)
1006  FORMAT(I4,1X,F6.3,2X,F8.3,2X,E12.5,2X,F6.1,2X,F7.5,2X,F7.1)
1007  FORMAT(I4,1X,F5.2,4(1X,E10.3),1X,F6.4)
1008  FORMAT(I4,1X,F6.3,2X,F8.6,4X,E10.3)
1009  FORMAT(I4,1X,F6.3,1X,3(1X,F7.1),2X,2(1X,F7.1),3X,F7.1)
1010  format(f6.3,2x,f9.1,3x,f8.5,3x,5(x,f8.5))
      qsum=0.0
      do 20 i=0,n
         qsum=qsum+qcv(i)
         write(10,2001)i*dz,h(i),td(i),tc(i),udz(i),hur(i),xd(i),
      #         r(i),rynld(i),bet(i)
20    continue
```

```
2001 format(f5.3,1x,f6.0,2(1x,f5.2),1x,f7.4,2(1x,f5.3),1x,f7.5,
    #       1x,f7.0,1x,f5.3)
      RETURN
      END
C-------------------------------------------------------------
      SUBROUTINE BBLMIX(RHODL,RHODV,XD,BETA)
      REAL M
      DIMENSION X(1)
      COMMON/BMIX/M,XQ
      XQ=XD
      M=RHODL/RHODV
      CALL NONEQN(1,X,.00001,.01,315,200,1.E-6)
      BETA=X(1)
      RETURN
      END
C-------------------------------------------------------------
      SUBROUTINE QUALCHCK(X)
      IF(X.LT.0.0) THEN
         X=0.0
      ELSEIF(X.GT.1.0)THEN
         X=1.0
      ENDIF
      RETURN
      END
C-------------------------------------------------------------
      SUBROUTINE TRNGCHK(ITR,TF)
      IF(ITR.EQ.1) THEN
         WRITE(*,*)'*********************************************'
         WRITE(*,*)'TEMPERATURE OUT OF RANGE:  One of the fluid'
         WRITE(*,*)'temperatures has exceeded the range limit in'
         WRITE(*,*)'one of the property routines.'
         WRITE(*,*)'*********************************************'
         WRITE(*,*)'FLUID TEMPERATURE=',TF
         WRITE(7,*)
         WRITE(7,*)
         WRITE(7,*)'*********************************************'
         WRITE(7,*)'TEMPERATURE OUT OF RANGE:  One of the fluid'
         WRITE(7,*)'temperatures has exceeded the range limit in'
         WRITE(7,*)'one of the property routines.'
         WRITE(7,*)'*********************************************'
         WRITE(7,*)'FLUID TEMPERATURE=',TF
         STOP
      ELSE
         RETURN
      ENDIF
      END
C-------------------------------------------------------------
      SUBROUTINE NONEQN (N,X,XXS,XINC,NINT,ITER,EPS)
      REAL M
      DIMENSION X(N)
      COMMON/BMIX/M,XQ
      XS=XXS
      CC=0.0
      DELX=0.0
      II=0
      NP=1
      A=F(XS)
      IF(A.NE.0.0 .AND. XS.NE. 0.0) GOTO 10
      II=II+1
      X(II)=0.0
      XS=XS+XINC
      A=F(XS)
```

```
10     AA=A
       A=F(XS)
       CC=AMAX1(XS,CC)
       IF(NP.GT.NINT) GOTO 50
       NP=NP+1
       AAA=A*AA
       XS=XS+XINC
       IF (AAA) 20,40,10
20     XS=XS-XINC
       XINCN=XINC/5.0
       I=1
30     B=F(XS)
       CON=(F(XS+XINCN)-F(XS))/XINCN
       DELX=B/CON
       XS=XS-DELX
       DELX=ABS(DELX)
       ITER1=I
       IF(DELX.LT.EPS) GOTO 40
       CC=AMAX1(XS,CC)
       I=I+1
       IF(I.GT.ITER) GOTO 40
       GOTO 30
40     II=II+1
       X(II)=XS
       XS=CC+XINC
       IF(II.GE.N) GOTO 50
       A=F(XS)
       IF(A.EQ.0.0) A=F(XS+XINC)
       XS=XS+XINC
       GOTO 10
50     CONTINUE
       RETURN
       END
C_____
       FUNCTION F(BETA)
       REAL M
       COMMON/BMIX/M,XQ
       F=3*COS(BETA)-(COS(BETA))**3+2-(4*(1-XQ))/(1+XQ*(M-1))
       RETURN
       END
C_____
       SUBROUTINE GINTGRT(EC,E,G)
       DTH=3.14159/100.
       G=0.
       DO 1 I=1,100
          TH=I*DTH-.5*DTH
          G=G+SIN(TH)**3*(1.-(1.-1./EC**4)*SIN(TH)**2)**.5/
     #        (1.-E**2*SIN(TH)**2)**(5./2.)*DTH
1      CONTINUE
       RETURN
       END
C_____
       SUBROUTINE H2OBETA(TC,BETA)
       T=TC+273.15
       BETA=-.0241253+.000199695*T-5.50632E-7*T**2
     #        +5.20287E-10*T**3
       RETURN
       END
C_____
       SUBROUTINE FLTHCAP(FTYPE,TF,PRESS,CP,RHO,Q,ITR)
       CHARACTER*6 FTYPE
       ITR=0
```

```
CP=0.0
RHO=0.0
Q=0.0
TLU=-300
TLL=-300
IF(FTYPE.EQ.'TH44   ') THEN
    TLL=-45
    TLU=260
    IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
    CP=2.47558*TF+1895.91
    RHO=940.03-0.75776*TF-1.2075E-4*TF**2
    Q=0.0
ELSEIF(FTYPE.EQ.'TH55   ') THEN
    TLL=0
    TLU=343.
    IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
    CP=3.38436*TF+1862.95
    RHO=895.12-0.66735*TF-6.1756E-6*TF**2
    Q=0.0
ELSEIF(FTYPE.EQ.'TH60   ') THEN
    TLL=-50.
    TLU=343.
    IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
    CP=1517.5+3.7058*TF
    RHO=1007.9-0.64663*TF-6.8946E-5*TF**2
    Q=0.0
ELSEIF(FTYPE.EQ.'TH66   ') THEN
    TLL=-18.
    TLU=371.
    IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
    CP=1514.7+3.5326*TF
    RHO=1020.3-0.67361*TF-2.7852E-5*TF**2
    Q=0.0
ELSEIF(FTYPE.EQ.'TH88   ') THEN
    TLL=149.
    TLU=482.
    IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
    CP=2.1984*TF+1627.2
    RHO=-1.2077E-4*TF**2-0.7389*TF+1121.2
    Q=0.0
ELSEIF(FTYPE.EQ.'DTSR1 ') THEN
    TLL=0.
    TLU=125.
    IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
    CP=3204.1+3.8701*TF
    RHO=1082.5-0.33961*TF-2.4148E-3*TF**2
    Q=0.0
ELSEIF(FTYPE.EQ.'DT4000') THEN
    TLL=4.
    TLU=177.
    IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
    CP=3169.2+3.9563*TF
    RHO=1096.7-0.491*TF-1.5049E-3*TF**2
    Q=0.0
ELSEIF(FTYPE.EQ.'DT4030') THEN
    TLL=4.
    TLU=176.
    IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
    CP=3741.2+1.5305*TF
    RHO=1061.6-.346849*TF-.00193194*TF**2
    Q=0.0
ELSEIF(FTYPE.EQ.'DT4040') THEN
```

```
      TLL=4.
      TLU=176.
      IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
      CP=3533.9+2.8283*TF-.00219331*TF**2
      RHO=1071.6-.34685*TF-.00193194*TF**2
      Q=0.0
ELSEIF(FTYPE.EQ.'DT4050') THEN
      TLL=4.
      TLU=176.
      IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
      CP=3321.4+3.49*TF-1.1506E-3*TF**2
      RHO=1092.4-.5401*TF-.0011855*TF**2
      Q=0.0
ELSEIF(FTYPE.EQ.'DT4060') THEN
      TLL=4.
      TLU=176.
      IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
      CP=3103.8+4.4285*TF-.0020395*TF**2
      RHO=1112.9-.754322*TF
      Q=0.0
ELSEIF(FTYPE.EQ.'DWFHD ') THEN
      TLL=4.
      TLU=177.
      IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
      CP=3297.7+5.0675*TF-4.9202E-3*TF**2
      RHO=1071.4-0.61005*TF-9.05E-4*TF**2
      Q=0.0
ELSEIF(FTYPE.EQ.'DFHD30') THEN
      TLL=4.
      TLU=162.
      IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
      CP=3894.6+1.7059*TF-2.2976E-3*TF**2
      RHO=1052.6-.587151*TF-6.4261E-4*TF**2
      Q=0.0
ELSEIF(FTYPE.EQ.'DFHD40') THEN
      TLL=4.
      TLU=162.
      IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
      CP=3736.9+2.3371*TF-2.11822E-3*TF**2
      RHO=1062.3-.51924*TF-.00142626*TF**2
      Q=0.0
ELSEIF(FTYPE.EQ.'DFHD50') THEN
      TLL=4.
      TLU=162.
      IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
      CP=3496.9+3.5702*TF-.0020608*TF**2
      RHO=1073-.757688*TF
      Q=0.0
ELSEIF(FTYPE.EQ.'DFHD60') THEN
      TLL=4.
      TLU=162.
      IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
      CP=3257+4.80134*TF-1.9952E-3*TF**2
      RHO=1072.3-.519239*TF-.00142626*TF**2
      Q=0.
ELSEIF(FTYPE.EQ.'DWFRST') THEN
      TLL=4.
      TLU=121.
      IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
      CP=3455.9+3.8394*TF
      RHO=1054.1-0.43901*TF-2.5735E-3*TF**2
      Q=0.0
```

```
ELSEIF(FTYPE.EQ.'PARANF') THEN
    TLL=10.
    TLU=316.
    IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
    CP=1810.9+3.5594*TF
    RHO=729.65-0.33504*TF
    Q=0.0
ELSEIF(FTYPE.EQ.'PARAHE') THEN
    TLL=10.
    TLU=316.
    IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
    CP=1876.8+4.1316*TF
    RHO=746.1-0.63119*TF
    Q=0.0
ELSEIF(FTYPE.EQ.'MTHVP1') THEN
    TLL=15.
    TLU=404.
    IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
    CP=1502.4+2.7206*TF
    RHO=1071.2-0.62931*TF-7.8203E-2*TF**2
    Q=0.0
ELSEIF(FTYPE.EQ.'CFAF  ') THEN
    TLL=40.
    TLU=316.
    IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
    CP=1714.9+3.8688*TF
    RHO=862.89-0.63225*TF+4.0234E-4*TF**2
    Q=0.0
ELSEIF(FTYPE.EQ.'CFFG  ') THEN
    TLL=40.
    TLU=288.
    IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
    CP=1803.8+3.3423*TF
    RHO=854.12-0.27305*TF-7.5461E-4*TF**2
    Q=0.0
ELSEIF(FTYPE.EQ.'CFHTF ') THEN
    TLL=40.
    TLU=316.
    IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
    CP=1845.8+3.2776*TF
    RHO=871.0-0.58587*TF+2.2249E-4*TF**2
    Q=0.0
ELSEIF(FTYPE.EQ.'SYLTH8') THEN
    TLL=-73.
    TLU=260.
    IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
    CP=1574.5+1.7067*TF
    RHO=955.89-0.81738*TF-4.8042E-4*TF**2
    Q=0.0
ELSEIF(FTYPE.EQ.'THM550') THEN
    TLL=-17.
    TLU=316.
    IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
    CP=1989.5+3.3681*TF
    RHO=852.91-0.67118*TF
    Q=0.0
ELSEIF(FTYPE.EQ.'THM600') THEN
    TLL=-17.
    TLU=327.
    IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
    CP=2094.7+3.1495*TF
    RHO=835.58-0.65347*TF
```

```
        Q=0.0
ELSEIF(FTYPE.EQ.'THM800') THEN
    TLL=-17.
    TLU=371.
    IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
    CP=2184.5+3.2144*TF-9.6370E-4*TF**2
    RHO=2184.5+3.2144*TF-9.6370E-4*TF**2
    Q=0.0
ELSEIF(FTYPE.EQ.'THRMX ') THEN
    IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
    CP=2.83089*TF+1528.32
    RHO=-.938571*TF+1089.29
    Q=0.0
ELSEIF(FTYPE.EQ.'AIR   ') THEN
    TLL=-173.
    TLU=2726.
    IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
    CP=1005.28+5.3251E-3*TF+6.337E-4*TF**2-8.1579E-7*TF**3
#       +4.9426E-10*TF**4-1.5492E-13*TF**5+2.3265E-17*TF**6
    IF(TF.LE.26.) THEN
        RHO=1.26941-4.886E-3*TF+2.5977E-5*TF**2+1.8185E-7*TF**3
#           +1.7867E-9*TF**4
    ELSEIF (TF.GT.26.0.AND.TF.LE.2225.) THEN
        RHO=1.26214-4.1154E-3*TF+1.011E-5*TF**2-1.6588E-8*TF**3
#           +1.7341E-11*TF**4-1.1284E-14*TF**5+4.3989E-18*TF**6
#           -9.3648E-22*TF**7+8.3467E-26*TF**8
    ELSEIF (TF.GT.2225.) THEN
        RHO=0.350535-1.313E-4*TF+1.6274E-8*TF**2
    ENDIF
    Q=1.0
ELSEIF(FTYPE.EQ.'CO2   ') THEN
    TLL=-53.
    TLU=1526
    IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
    CP=827.967+0.99954*TF-8.4763E-4*TF**2+3.8487E-7*TF**3
#       -7.1375E-11*TF**4
    RHO=1.9713-5.8952E-3*TF+9.8244E-6*TF**2-7.5549E-9*TF**3
#       +2.0916E-12*TF**4
    Q=1.0
ELSEIF(FTYPE.EQ.'H2    ') THEN
    TLL=-173.
    TLU=1726.
    IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
    CP=14183.4+5.5081*TF-.037213*TF**2+1.2355E-4*TF**3
#       -2.2182E-7*TF**4+2.3445E-10*TF**5-1.4451E-13*TF**6
#       +4.77946E-17*TF**7-6.51397E-21*TF**8
    RHO=.087964-3.0046E-4*TF+1.247E-6*TF**2-6.5073E-9*TF**3
#       +2.4773E-11*TF**4-5.7169E-14*TF**5+8.0088E-17*TF**6
#       -6.8746E-20*TF**7+3.5342E-23*TF**8-9.9886E-27*TF**9
#       +1.19331E-30*TF**10
    Q=1.0
ELSEIF(FTYPE.EQ.'N2    ') THEN
    TLL=-173.
    TLU=1026.
    IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
    CP=1039.9-.033984*TF+6.0155E-4*TF**2-5.3704E-7*TF**3
#       +1.4479E-10*TF**4
    RHO=1.2826-4.5158E-3*TF+1.0512E-5*TF**2-5.0297E-8*TF**3
#       +4.2596E-10*TF**4-1.8193E-12*TF**5+3.9745E-15*TF**6
#       -4.6671E-18*TF**7+2.8145E-21*TF**8-6.8517E-25*TF**9
    Q=1.0
ELSEIF(FTYPE.EQ.'O2    ') THEN
```

```
      TLL=-173.
      TLU=1026.
      IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
      CP=913.86+.090997*TF+.0013194*TF**2-3.1674E-6*TF**3
#         +3.00295E-9*TF**4-1.03672E-12*TF**5
      RHO=1.4662-5.1602E-3*TF+1.1947E-5*TF**2-5.7867E-8*TF**3
#         +4.9429E-10*TF**4-2.114E-12*TF**5+4.6193E-15*TF**6
#         -5.4242E-18*TF**7+3.2709E-21*TF**8-7.9618E-25*TF**9
      Q=1.0
  ELSEIF(FTYPE.EQ.'NH3   ') THEN
      TLL=-100
      TLU=406.
      IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
      CP=2134.76+.538392*TF+.0063678*TF**2-9.9898E-6*TF**3
      RHO=.73673-.00209815*TF+2.8379E-6*TF**2
      Q=1.0
  ELSEIF(FTYPE.EQ.'MS20  ') THEN
      CP=3.09412*TF+1980.44
      RHO=-0.56681*TF+903.679
      Q=0.0
  ELSEIF(FTYPE.EQ.'TRAN  ') THEN
      CP=-1.5597E-9*TF**6+3.6213E-7*TF**5-1.7345E-5*TF**4
#         -1.4121E-3*TF**3+.12049*TF**2+3.04729*TF+1616.47
      RHO=-.62105*TF+891.364
      Q=0.0
  ELSEIF(FTYPE.EQ.'TM1   ') THEN
      CP=(.00120508*TF+1.61848)*1000.
      RHO=-0.63744*TF+902.499
      Q=0.0
  ELSEIF(FTYPE.EQ.'VM4   ') THEN
      CP=-2.3592E-9*TF**6+5.4339E-7*TF**5-3.7219E-5*TF**4
#         +3.022E-4*TF**3+0.04831*TF**2+.23315*TF+1457.74
      RHO=-0.5915*TF+915.492
      Q=0.0
  ELSEIF(FTYPE.EQ.'KHF22 ') THEN
      CP=-1.58271E-6*TF**4+6.52884E-5*TF**3+0.012453*TF**2
#         +.241957*TF+1638.96
      RHO=-0.72984*TF+1009.52
      Q=0.0
  ELSEIF(FTYPE.EQ.'ENG   ') THEN
      TLL=0.
      TLU=156.
      IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
      CP=1798.42+4.06543*TF+.001455*TF**2
      RHO=899.55-.5926*TF
      Q=0.0
  ELSEIF(FTYPE.EQ.'ETHYLG') THEN
      TLL=0
      TLU=100.
      IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
      CP=2293.78+4.4801*TF
      RHO=1129.76-.23264*TF-.026345*TF**2+4.5083E-4*TF**3
#         -2.3342E-6*TF**4
      Q=0.0
  ELSEIF(FTYPE.EQ.'GLYCRN') THEN
      TLL=0
      TLU=46
      IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
      CP=2260.92+5.8326*TF+.01288*TF**2
      RHO=1275.52-.5666*TF-7.2682E-4*TF**2
      Q=0.0
  ELSEIF(FTYPE.EQ.'HG    ') THEN
```

```
            TLL=0
            TLU=326
            IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
            CP=1403.48-.3996*TF+7.7106E-4*TF**2
            RHO=13592.9-2.4009*TF
            Q=0.0
         ENDIF
         GOTO 1
100      ITR=1
         GOTO 2
1        IF(Q.EQ.1.0) RHO=RHO*PRESS/101.325
2        RETURN
         END
C
C
C====================================================================
C====================================================================
C
         SUBROUTINE PROPTY(FTYPE,TF,PRC,CKL,CKV,VISL,VISV,SIG,ITR)
C        *****************************************************************
C                THERMOPHYSICAL PROPERTIES PF
C                WATER,AIR,N-PENTANE,BUTANE,ISOBUTANE
C                PROPERTIES:
C                HYDROCARBON:  LIQUID,VAPOR KINEMATIC VIS.
C                          LIQUID,VAPOR THERMAL CONDUCTIVITY
C                          SURFACE TENSION
C                WATER  : LIQUID KINEMATIC VISCOSITY
C                          LIQUID THERMAL CONDUCTIVITY
C                          SURFACE TENSION
C                AIR    : KINEMATIC VISCOSITY
C                          THERMAL CONDUCTIVITY
C
C                REFERENCE :  Tables of Thermophysical Properties
C                of Liquids and Gases,   N.B. Vargaftic
C        *****************************************************************
C                REFERENCE COBAN DISSERT FOR VARIABLE DEF.
         CHARACTER*6 FTYPE
C
         ITR=0
         VISV=0.
         VISL=0.
         CKV=0.
         CKL=0.
         SIG=0.
C
         IF(FTYPE.EQ.'H2O    ') THEN
         IF(PRC.LT.2.E06) THEN
         IF(TF.LT.100) THEN
C P = 1 BAR
         A0=.5689999177E00
         A1=.2237388258E-02
         A2=-.4194219792E-04
         A3=.8461035643E-06
         A4=-.1064290936E-08
         A5=-.2195261464E-09
         A6=.2867647080E-11
         A7=-.1109E-13
         CK1=A0+A1*TF+A2*TF**2+A3*TF**3+A4*TF**4+A5*TF**5+
        #  A6*TF**6+A7*TF**7
C P = 20 BARS
         A0=.5000276018E00
         A1=.1842722906E-01
```

```
           A2=-.1449807789E-02
           A3=.6254021227E-04
           A4=-.1490806953E-05
           A5=.1984199371E-07
           A6=-.1381372569E-09
           A7=.3915733022E-12
           CK2=A0+A1*TF+A2*TF**2+A3*TF**3+A4*TF**4+A5*TF**5+
         #  A6*TF**6+A7*TF**7
           CKL=CK1+(CK2-CK1)/(1.9E+06)*(PRC-.1E+06)
             CKV=0.0
           ELSE
C    P = 20 BARS
           A0=.5034354585E00
           A1=.1080602021E-01
           A2=-.4031109874E-03
           A3=.81871132370E-05
           A4=-.8981143005E-07
           A5=.5378607955E-09
           A6=-.1659310095E-11
           A7=.206279238E-14
           CK2=A0+A1*TF+A2*TF**2+A3*TF**3+A4*TF**4+A5*TF**5+
         #  A6*TF**6+A7*TF**7
           CKL=CK2
           CKV=0.0
           ENDIF
           ELSE
C    P=20 BARS
           A0=.5034354585E00
           A1=.1080602021E-01
             A2=-.4031109874E-03
           A3=.81871121370E-05
           A4=-.8981143005E-07
           A5=.5378607955E-09
           A6=-.165931009E-11
           A7=.20627923E-14
           CK1=A0+A1*TF+A2*TF**2+A3*TF**3+A4*TF**4+A5*TF**5+
         #  A6*TF**6+A7*TF**7
C    P = 40 BARS
           A0=.5719129275E00
           A1=.1915405391E-02
           A2=-.8020192384E-05
           A3=-.2277327713E-07
           A4=.4561862413E-09
           A5=-.3196354991E-11
           A6=.1089066733E-13
           A7=-.1478755907E-16
           CK2=A0+A1*TF+A2*TF**2+A3*TF**3+A4*TF**4+A5*TF**5+
         #  A6*TF**6+A7*TF**7
           CKL=CK1+(CK2-CK1)/(2.E+06)*(PRC-2.E+06)
           CKV=0.0
           ENDIF
           IF(PRC.LT.2.E06) THEN
           IF(TF.LT.100) THEN
C    P = 1 BAR
           A0=.1752498865E+05
           A1=-.5623342898E+03
           A2=.1293770770E+02
           A3=-.2316151658E00
           A4=.3092855426E-02
           A5=-.2800988617E-04
           A6=.1494852986E-06
           A7=-.3495565033E-09
```

```
        VIS1=A0+A1*TF+A2*TF**2+A3*TF**3+A4*TF**4+A5*TF**5+
      #   A6*TF**6+A7*TF**7
C       P = 20 BARS
        A0=.1751398227E+05
        A1=-.5621437186E+03
        A2=.1301016255E+02
        A3=-.2372883464E+00
        A4=.32728885154E-02
        A5=-.3108219012E-04
        A6=.1745751680E-06
        A7=-.4300887168E-09
        VIS2=A0+A1*TF+A2*TF**2+A3*TF**3+A4*TF**4+A5*TF**5+
      #   A6*TF**6+A7*TF**7
        VISL=VIS1+(VIS2-VIS1)/(1.9E+06)*(PRC-.1E+06)
        VISL=VISL*1.E-07
          VISV=0.0
        ELSE
C       P = 20 BARS
        A0=.4230490200E+04
        A1=.1884581715E+03
        A2=-.667610027E+01
        A3=.9206814826E-01
        A4=-.6904918772E-03
        A5=.2967543200E-05
        A6=-.6887934270E-08
        A7=.6712245273E-11
        VIS2=A0+A1*TF+A2*TF**2+A3*TF**3+A4*TF**4+A5*TF**5+
      #   A6*TF**6+A7*TF**7
        VISL=VIS2*1.E-07
        VISV=0.0
        ENDIF
        ELSE
        IF(TF.LT.100) THEN
C       P = 20 BARS
        A0=.17513982270E+05
        A1=-.5621437186E+03
        A2=.1301016255E+02
        A3=-.2372883464E+00
        A4=.3278885154E-02
        A5=-.3108219012E-04
        A6=.1745751680E-06
        A7=-.4300887168E-09
        VIS1=A0+A1*TF+A2*TF**2+A3*TF**3+A4*TF**4+A5*TF**5+
      #   A6*TF**6+A7*TF**7
C       P = 40 BARS
        A0=.1750199191E+05
        A1=-.5612118941E+03
        A2=.1295640067E+02
        A3=-.2346663975E+00
        A4=.3202648351E-02
        A5=.2986536004E-04
        A6=.1646732071E-06
        A7=-.3979925446E-09
        VIS2=A0+A1*TF+A2*TF**2+A3*TF**3+A4*TF**4+A5*TF**5+
      #   A6*TF**6+A7*TF**7
        VISL=VIS1+(VIS2-VIS1)/(2.E+06)*(PRC-2.E+06)
        VISL=VISL+1.E-07
          VISV=0.0
        ELSE
C       P = 20 BARS
        A0=.4230490200E+04
        A1=.1884581715E+03
```

```
           A2=-.667610027E+01
           A3=.9206814826E-01
           A4=-.6904918772E-03
           A5=.2967543200E-05
           A6=-.6887934270E-08
           A7=.6712245273E-11
           VIS1=A0+A1*TF+A2*TF**2+A3*TF**3+A4*TF**4+A5*TF**5+
     #     A6*TF**6+A7*TF**7
C    P = 40 BARS
           A0=.9542057174E+04
           A1=-.7263813086E+02
           A2=-.1240393524E+01
           A3=.2999460681E-01
           A4=-.2705631795E-03
           A5=.1284340755E-05
           A6=-.31852135E-08
           A7=.3261966188E-11
              VIS2=A0+A1*TF+A2*TF**2+A3*TF**3+A4*TF**4+A5*TF**5+
     #   A6*TF**6+A7*TF**7
        VISL=VIS1+(VIS2-VIS1)/(2.E+06)*(PRC-2.E+06)
        VISL=VISL*1.E-07
           VISV=0.0
        ENDIF
           ENDIF
           SIG=75.50411188811198-8.46835E-02*TF-3.187966E-03*TF**2
     #     +5.076282E-05*TF**3-3.326923E-07*TF**4+6.025641E-10*TF**5
           SIG=SIG*1.E-03
        ELSEIF(FTYPE.EQ.'AIR   ') THEN
           TLL=-173.
           TLU=2726.
           IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
           VISV=1.71833E-5+5.0923E-8*TF-3.8357E-11*TF**2+2.8467E-14*
     #        TF**3-9.9701E-18*TF**4+1.3181E-21*TF**5
           VISL=0.0
           CKV=0.0254297+8.3037E-5*TF-9.6375E-8*TF**2+1.286E-10*TF**3
     #        -7.3051E-14*TF**4+1.5801E-17*TF**5
           CKL=0.0
           SIG=0.0
        ELSEIF(FTYPE.EQ.'CO2   ') THEN
           TLL=-53.
           TLU=1526.
           IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
           VISV=1.4589E-5+3.8088E-8*TF-6.2015E-12*TF**2
           VISL=0.
           CKV=1.4448E-2+8.3527E-5*TF-1.3133E-8*TF**2
           CKL=0.
           SIG=0.
        ELSEIF(FTYPE.EQ.'H2    ') THEN
           TLL=-173.
           TLU=1726.
           IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
           VISL=0.
           VISV=8.26065E-6+2.0427E-8*TF-6.8867E-12*TF**2+1.7348E-15*TF**3
           CKL=0.
           CKV=.167244+4.9794E-4*TF-3.0927E-7*TF**2+2.6862E-10*TF**3
     #        -6.87395E-14*TF**4
           SIG=0.
        ELSEIF(FTYPE.EQ.'N2    ') THEN
           TLL=-173.
           TLU=1026.
           IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
           VISL=0.
```

```
        VISV=1.6277E-5+4.7868E-8*TF-2.9288E-11*TF**2+1.1255E-14*TF**3
        CKL=0.
        CKV=.023643+7.4477E-5*TF-3.9978E-8*TF**2+2.1437E-11*TF**3
        SIG=0.
   ELSEIF(FTYPE.EQ.'O2     ') THEN
        TLL=-173.
        TLU=1026.
        IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
        VISL=0.
        VISV=1.90145E-5+5.8246E-8*TF-4.16376E-11*TF**2
#          +2.14079E-14*TF**3
        CKL=0.
        CKV=.0235842+7.58894E-5*TF-1.43399E-8*TF**2
        SIG=0.
   ELSEIF(FTYPE.EQ.'NH3    ') THEN
        TLL=26.
        TLU=306.
        IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
        VISL=0.
        VISV=9.1404E-6+3.80243E-8*TF-9.0094E-12*TF**2
        CKL=0.
        CKV=.022197+8.65576E-5*TF+3.232E-7*TF**2-5.4597E-10*TF**3
        SIG=0.
   ELSEIF(FTYPE.EQ.'PENT   ') THEN
        CKV=11.7000943+.0974954646*TF+1.2506797E-04*TF**2
#       -3.20993285E-10*TF**3
        CKV=CKV*1.E-03
        CKL=.120500001-2.19166518E-04*TF-1.4583602E-06*TF**2
#       +4.1667695E-08*TF**3-4.16677821E-10*TF**4
        VISL=.2830648416302071-4.7037877074119475E-03*TF
#       +3.9457157378790382E-04*TF**2-2.2040828809048E-05*TF**3
#       +5.80420663296576E-07*TF**4-7.8134559782743E-09*TF**5
#       +5.2357026915869730E-11*TF**6-1.3865546463192681E-13*TF**7
        VISL=VISL*1.E-03
        VISV=49.3702925+.938695079*TF-.0151413279*TF**2
#       +1.38067486E-04*TF**3-4.01657705E-07*TF**4
        VISV=VISV*1.E-07
        SIG=18.200088-.104142117*TF-1.05600806E-03*TF**2
#       +5.42164101E-05*TF**3-7.87026653E-07*TF**4
        SIG=SIG*1.E-03
   ELSEIF(FTYPE.EQ.'BUT    ') THEN
        CKV=-4.3704E-11*TF**3+1.01398E-7*TF**2+.000108024*TF
#       +.01310114
        CKL=-7.81255E-10*TF**4+2.60419E-7*TF**3-3.21878E-5*TF**2
#       +.00149585*TF+.0749995
        VISL=-8.41033E-14*TF**5+3.28754E-11*TF**4-5.00885E-9*TF**3
#       +3.7359e-7*TF**2-1.47048*TF+.000376398
        VISV=-7.04548e-18*TF**5+6.15458e-15*TF**4-2.03319e-12*TF**3
#       +2.99428e-10*TF**2+5.54933e-9*TF+7.46943e-6
        SIG=5.30302E-11*TF**4+1.46969E-8*TF**3+1.52878E-6*TF**2
#       -5.55336E-5*TF+.0157512
   ELSEIF(FTYPE.EQ.'ISOP   ') THEN
        VISL=-1.66661e-10*TF**3+1.99997E-8*TF**2-2.78333E-6*TF
#       +.000272
        VISV=-2.09459E-12*TF**2+2.224021E-8*TF+6.38969E-6
        CKL=-8.88886E-8*TF**3+4.63094E-6*TF**2-.000298849*TF
#+.11906
        CKV=14.02360414148952+.1208272189021553*TF
#       +1.08600139039942589E-04*TF**2-1.9940388279179968E-05*TF**3
#       +4.9048950395836884E-07*TF**4-4.9294337623331529E-09*TF**5
#       +2.2305489177839495E-11*TF**6-3.7421511943571895E-14*TF**7
        CKV=CKV*1.E-03
```

```
      SIG=6.71858E-8*TF**2-.00010998*TF+.0171699
      ELSEIF(FTYPE.EQ.'ISOB  ') THEN
      VISL=1.55136E-10*TF**3-6.16567E-9*TF**2-2.09543E-6*TF
    # +.000214
      VISV=-4.35675E-14*TF**4+1.22251E-11*TF**3
    # -1.22875E-9*TF**2+7.04506E-8*TF+6.17173E-6
      SIG=6.78573E-8*TF**2-.000115583*TF+.0129523
C PROBLEM  : CKISV.DAT
      A0=.13813870E+02
      A1=.1088360E+00
      A2=.3069733333E-03
      A3=-.334880E-05
      A4=.1116266667E-07
      CKV=A0+A1*TF+A2*TF**2+A3*TF**3+A4*TF**4
      CKV=CKV*1.E-03
C PROBLEM  :CKESL
      A0=.10545730E+02
      A1=-.58977750E-01
      A2=.27657500E-03
      CKL=A0+A1*TF+A2*TF**2
      CKL=CKL*1.E-02
      ELSEIF (FTYPE.EQ.'HEP   ') THEN
          TLL=-90.
          TLU=400.
          IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
          CKL=.13420-2.7167E-4*TF+4.8701E-8*TF**2
          CKV=8.8553E-3+9.2249E-5*TF+7.1772E-8*TF**2
          IF(TF.LE.20.) THEN
              VISL=5.2757E-4-7.8221E-6*TF+5.2534E-8*TF**2+1.9301E-9*
    #             TF**3+5.5358E-11*TF**4
          ELSE
              VISL=5.2757E-4-7.8221E-6*20+5.2534E-8*20**2+1.9301E-9*
    #             20**3+5.5358E-11*20**4
          ENDIF
          VISV=5.3255E-6+2.0043E-8*TF+2.6577E-13*TF**2
          SIG=0.
      ELSEIF(FTYPE.EQ.'METH  ') THEN
          TLL=-173.
          TLU=83.
          IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
          CKL=.23242+4.6197E-3*TF+4.2448E-5*TF**2+9.6463E-8*TF**3
          CKV=.030875+1.3364E-4*TF+9.8656E-8*TF**2
          VISL=6.7496E-5+1.4941E-6*TF+1.1267E-8*TF**2
          VISV=1.025E-5+3.2756E-8*TF-1.8745E-11*TF**2
          SIG=0.
      ELSEIF(FTYPE.EQ.'ETHYL ') THEN
          TLL=-165.
          TLU=225.
          IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
          VISL=-2.3585E-3-6.3783E-5*TF-5.527E-7*TF**2-1.6643E-9*TF**3
          VISV=9.4809E-6+3.2084E-8*TF-1.1608E-11*TF**2
          CKL=8.1027E-2-1.2232E-3*TF-1.2078E-6*TF**2
          CKV=1.6976E-2+1.2134E-4*TF+1.2177E-7*TF**2
          SIG=0.
      ELSEIF(FTYPE.EQ.'MS20  ') THEN
        CKL=8.57848E-8*TF**2-1.19191E-4*TF+.136087
        CKV=0.0
        VISL=4331.33*TF**(-2.69759)
      VISV=0.0
      SIG=0.0
      ELSEIF(FTYPE.EQ.'TRAN  ') THEN
      CKL=-8.19549e-5*TF+.112297
```

```
      CKV=0.0
      VISL=.0406485*EXP(-.032348*TF)
      VISV=0.0
      SIG=0.0
      ELSEIF(FTYPE.EQ.'TM1    ') THEN
      CKL=-9.53055E-5*TF+.120687
      CKV=0.0
      VISL=.382997*TF**(-1.08805)
      VISV=0.0
      SIG=0.0
      ELSEIF(FTYPE.EQ.'VM4    ') THEN
      CKL=-8.94004E-5*TF+.129112
      CKV=0.0
      VISL=61.3841*TF**(-1.85956)
      VISV=0.0
      SIG=0.0
      ELSEIF(FTYPE.EQ.'KHF22 ') THEN
      CKL=-1.48464E-4*TF+.157694
      CKV=0.0
      VISL=2.57617*TF**(-1.30322)
      VISV=0.0
      SIG=0.0
      ELSEIF(FTYPE.EQ.'TH44   ') THEN
         TLL=-45.
         TLU=260.
         IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
         CKL=1.4566E-1-1.2663E-4*TF-1.5176E-7*TF**2
         IF(TF.LT.10.) THEN
            VISL=.0168827*EXP(-.0876271*TF)
         ELSEIF(TF.GE.10) THEN
            VISL=.014207-5.84755E-4*TF+1.1979E-5*TF**2-1.409E-7*TF**3
     #        +9.8367E-10*TF**4-4.01099E-12*TF**5+8.80257E-15*TF**6
     #        -8.0192E-18*TF**7
         ENDIF
         CKV=0.0
         VISV=0.0
         SIG=0.0
      ELSEIF(FTYPE.EQ.'TH55   ') THEN
         TLL=0.
         TLU=343.
         IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
         CKL=.130426-8.3889E-5*TF-1.17235E-7*TF**2
         CKV=0.0
         IF(TF.LT.38.) THEN
            VISL=.301559*EXP(-.0713115*TF)
         ELSEIF(TF.GE.38.) THEN
            VISL=.104613-3.9908E-3*TF+7.0359E-5*TF**2-7.1588E-7*TF**3
     #        +4.5138E-9*TF**4-1.7912E-11*TF**5+4.3535E-14*TF**6
     #        -5.9175E-17*TF**7+3.444E-20*TF**8
         ENDIF
         VISV=0.0
         SIG=0.0
      ELSEIF(FTYPE.EQ.'TH60   ') THEN
         TLL=-50.
         TLU=343.
         IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
         CKL=.13363-7.6511E-5*TF-3.6863E-9*TF**2
         CKV=0.0
         IF(TF.LT.10.) THEN
            VISL=.0233656*EXP(-.0841699*TF)
         ELSEIF(TF.GE.10.) THEN
            VISL=.019873-8.1667E-4*TF+1.7149E-5*TF**2-2.0926E-7*TF**3
```

```
#              +1.554E-9*TF**4-7.1014E-12*TF**5+1.9461E-14*TF**6
#              -2.9291E-17*TF**7+1.8593E-20*TF**8
       ENDIF
       VISV=0.0
       SIG=0.0
    ELSEIF(FTYPE.EQ.'TH66   ') THEN
       TLL=-18
       TLU=371
       IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
       CKL=.120973-5.08537E-5*TF-1.06489E-7*TF**2
       CKV=0.0
       IF(TF.LT.49) THEN
          VISL=.928583*EXP(-.0891155*TF)
       ELSE
          VISL=14.3448*TF**(-1.79827)
          ENDIF
       VISV=0.0
       SIG=0.0
    ELSEIF(FTYPE.EQ.'TH88   ') THEN
       TLL=149
       TLU=482
       IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
       CKL=.139621-7.9469E-5*TF-2.8337E-9*TF**2
       CKV=0.
       VISL=3.6914*TF**(-2.01174)
       VISV=0.
       SIG=0.
    ELSEIF(FTYPE.EQ.'CFAF   ') THEN
       TLL=40
       TLU=316.
       IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
       VISL=39.7783*TF**(-1.99202)
       CKL=.13807-5.4571E-5*TF+1.7361E-9*TF**2
       CKV=0.
       SIG=0.
    ELSEIF(FTYPE.EQ.'CFFG   ') THEN
       TLL=40
       TLU=288.
       IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
       VISL=3.62695*TF**(-1.55491)
       VISV=0.
       CKL=.13913-8.5789E-5*TF+9.1377E-8*TF**2
       CKV=0.
       SIG=0.
    ELSEIF(FTYPE.EQ.'CFHTF  ') THEN
       TLL=40
       TLU=316.
       IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
       VISL=50.8759*TF**(-2.00572)
       VISV=0.
       CKL=.13907-5.4571E-5+1.7361E-9*TF**2
       CKV=0.
       SIG=0.
    ELSEIF(FTYPE.EQ.'SYLTH8') THEN
       TLL=-73
       TLU=260.
       IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
       IF(TF.LT.10) THEN
          VISL=.00220438-3.9223E-5*TF-4.6422E-7*TF-2.5722E-8*TF**3
       ELSE
          VISL=.00202134-3.07134E-5*TF+2.34941E-7*TF**2
#              -8.7194E-10*TF**3+1.22576E-12*TF**4
```

```
      ENDIF
      VISV=0.
      CKL=.10792-6.52567E-5*TF+1.74916E-9*TF**2
      CKV=0.
      SIG=0.
   ELSEIF(FTYPE.EQ.'PARAHE') THEN
      TLL=10.
      TLU=316.
      IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
      VISL=795.75*TF**(-2.70403)
      VISV=0.
      CKL=0.13455-7.4724E-5*TF
      CKV=0.
      SIG=0.
   ELSEIF(FTYPE.EQ.'PARANF') THEN
      TLL=10.
      TLU=316.
      IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
      VISL=4.40572*TF**(-1.60423)
      VISV=0.
      CKL=.13431-7.0226E-5*TF
      CKV=0.
      SIG=0.
   ELSEIF(FTYPE.EQ.'MTHVP1') THEN
      TLL=15.
      TLU=404.
      IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
      VISL=.00792082-2.0877E-4*TF+2.9702E-6*TF**2-2.6742E-8*TF**3
#         +1.5734E-10*TF**4-5.9706E-13*TF**5+1.3963E-15*TF**6
#         -1.8196E-18*TF**7+1.0071E-21*TF**8
      VISV=0.
      CKL=.143285-1.53527E-4*TF+2.03924E-8*TF**2
      CKV=0.
      SIG=0.
   ELSEIF(FTYPE.EQ.'THM550') THEN
      TLL=-17.
      TLU=316.
      IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
      CKL=1.4486E-1-7.4074E-5*TF
      CKV=0.
      IF(TF.LT.4.5) THEN
          VISL=.184015*EXP(-.0602736*TF)
      ELSE
          VISL=.174439-8.1538E-3*TF+1.8709E-4*TF**2-2.5991E-6*TF**3
#         +2.3307E-8*TF**4-1.37384E-10*TF**5+5.27456E-13*TF**6
#         -1.2669E-15*TF**7+1.72579E-18*TF**8-1.01648E-21*TF**9
      ENDIF
      VISV=0.
      SIG=0.
   ELSEIF(FTYPE.EQ.'THM600') THEN
      TLL=-17.
      TLU=327.
      IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
      IF(TF.LT.4.5) THEN
          VISL=.182273*EXP(-.0732021*TF)
      ELSE
          VISL=.170328-8.7649E-3*TF+2.1606E-4*TF**2-3.1393E-6*TF**3
#         +2.8835E-8*TF**4-1.716E-10*TF**5+6.5874E-13*TF**6
#         -1.5717E-15*TF**7+2.1173E-18*TF**8-1.2293E-21*TF**9
      ENDIF
      VISV=0.
      CKL=.15629-6.196E-5*TF
```

```
      CKV=0.
      SIG=0.
   ELSEIF(FTYPE.EQ.'THM800') THEN
      TLL=-17.
      TLU=371.
      IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
      VISL=.126335-6.0631E-3*TF+1.1617E-4*TF**2-1.134E-6*TF**3
#          +6.1506E-9*TF**4-1.8752E-11*TF**5+3.00614E-14*TF**6
#          -1.971E-17*TF**7
      VISV=0.
      CKL=.1529-1.0318E-4*TF-7.4183E-9*TF**2
      CKV=0.
      SIG=0.
   ELSEIF(FTYPE.EQ.'THRMX ') THEN
      CKL=-1.3333E-4*TF+.14319
      CKV=0.0
      VISL=.27911*TF**(-1.23818)
      VISV=0.0
      SIG=0.0
   ELSEIF(FTYPE.EQ.'DTSR1') THEN
      TLL=0.
      TLU=125.
      IF(TF.LE.TLL.OR.TF.GT.TLU) GOTO 100
      CKL=.363+9.09344E-4*TF-3.81547E-6*TF**2
      CKV=0.0
      VISL=.00733697-1.23288E-4*TF+5.53221E-7*TF**2
      VISV=0.0
      SIG=0.0
   ELSEIF(FTYPE.EQ.'DT4000') THEN
      TLL=4.
      TLU=177.
      IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
      VISL=.00746199-1.53974E-4*TF+1.4021E-6*TF**2-2.825E-9*TF**3
      VISV=0.
      CKL=.362926+9.2063E-4*TF-3.91495E-6*TF**2
      CKV=0.
      SIG=0.
   ELSEIF(FTYPE.EQ.'DT4030') THEN
      TLL=4.
      TLU=176.
      IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
      VISL=-8.3167E-4*LOG(TF)+.00441
      VISV=0.0
      CKL=.437696+1.24698E-3*TF-4.8875E-6*TF**2
      CLV=0.
      SIG=0.
   ELSEIF(FTYPE.EQ.'DT4040') THEN
      TLL=4.
      TLU=176.
      IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
      VISL=-.00116578*LOG(TF)+.00609
      VISV=0.
      CKL=.403952+.001046*TF-4.1122E-6*TF**2
      CKV=0.
      SIG=0.
   ELSEIF(FTYPE.EQ.'DT4050') THEN
      TLL=4.
      TLU=176.
      IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
      VISL=-.00161257*LOG(TF)+.0083384
      VISV=0.
      CKL=.3719+8.4555E-4*TF-3.3368E-6*TF**2
```

```
            CKV=0.
            SIG=0.
      ELSEIF(FTYPE.EQ.'DT4060') THEN
            TLL=4.
            TLU=176.
            IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
            VISL=.0323917*TF**(-.866)
            VISV=0.
            CKL=.339419+7.60199E-4*TF-2.8656E-6*TF**2
            CKV=0.
            SIG=0.
      ELSEIF(FTYPE.EQ.'DWFRST') THEN
            TLL=4.
            TLU=121.
            IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
            VISL=.0152155-2.79327E-4*TF+1.30927E-6*TF**2
            VISV=0.
            CKL=.349979+7.25542E-4*TF-4.00611E-6*TF**2
            CKV=0.
            SIG=0.
      ELSEIF(FTYPE.EQ.'DWFHD ') THEN
            TLL=4.
            TLU=176.
            IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
            VISL=.0155255-3.5542E-4*TF+2.765E-6*TF**2-7.0061E-9*TF**3
            VISV=0.
            CKL=.34947+8.504E-4*TF-6.3946E-6*TF**2+1.1496E-7*TF**3
            CKV=0.
            SIG=0.
      ELSEIF(FTYPE.EQ.'DFHD30') THEN
            TLL=4.
            TLU=162.
            IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
            VISL=.5*(.004767*EXP(-.018319*TF)+.018137*TF**(-.780412))
            VISV=0.
            CKL=.4205+.0012295*TF-5.4564E-6*TF**2
            CKV=0.
            SIG=0.
      ELSEIF(FTYPE.EQ.'DFHD40') THEN
            TLL=4.
            TLU=162.
            IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
            VISL=.5*(.0077474*EXP(-.020585*TF)+.0352158*TF**(-.880378))
            VISV=0.
            CKL=.38+9.759E-4*TF-4.0706E-6*TF**2
            CKV=0.
            SIG=0.
      ELSEIF(FTYPE.EQ.'DFHD50') THEN
            TLL=4.
            TLU=162.
            IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
            VISL=.5*(.0117985*EXP(-.022392*TF)+.0601634*TF**(-.952745))
            VISV=0.
            CKL=.34087+8.2641E-4*TF-3.3728E-6*TF**2
            CKV=0.
            SIG=0.
      ELSEIF(FTYPE.EQ.'DFHD60') THEN
            TLL=4.
            TLU=162.
            IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
            VISL=.5*(.0194357*EXP(-.025182*TF)+.123987*TF**(-1.07719))
            VISV=0.
```

```
        CKL=.30883+6.3162E-4*TF-2.6656E-6*TF**2
        CKV=0.
        SIG=0.
      ELSEIF(FTYPE.EQ.'F11    ') THEN
        TLL=0.
        TLU=150.
        IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
        CKL=9.5768E-2-2.4018E-4*TF+4.7302E-8*TF**2
        CKV=8.1527E-3+2.3475E-5*TF+1.8628E-7*TF**2
        VISL=5.6689E-4-6.5163E-6*TF+3.436E-8*TF**2-7.393E-11*TF**3
        VISV=1.0179E-5+3.0692E-8*TF+9.3987E-11*TF**2
        SIG=0.0
      ELSEIF(FTYPE.EQ.'F12    ') THEN
        TLL=0.
        TLU=100.
        IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
        CKL=-.00036907*TF+.07839
        CKV=4.8866E-13*TF**5+1.4967E-12*TF**4-3.415E-9*TF**3
     #       +5.697E-8*TF**2+5.5499E-5*TF+.008341
        VISL=4.4004E-13*TF**4-2.1957E-10*TF**3+2.3831E-8*TF**2
     #       -2.3225E-6*TF+.00026543
        VISV=4.6615E-14*TF**4+2.8129E-13*TF**3-1.31961E-10*TF**2
     #       +4.7197E-8*TF+1.1779E-5
        SIG=0.0
      ELSEIF(FTYPE.EQ.'F13    ') THEN
        TLL=0.
        TLU=100.
        IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
        CKL=5.3061E-2-2.9112E-4*TF+1.7371E-6*TF**2
        CKV=1.3605E-2+1.5381E-4*TF+7.7252E-7*TF**2
        VISL=1.0132E-4-3.6831E-7*TF+2.8835E-8*TF**2
        VISV=1.4922E-5+1.163E-7*TF+1.2104E-9*TF**2+8.2369E-12*TF**3
        SIG=0.0
      ELSEIF(FTYPE.EQ.'F22    ') THEN
        TLL=-20.
        TLU=60.
        IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
        CKL=9.6174e-2-4.2368e-4*TF+3.4954e-7*TF**2
        CKV=9.5013E-3+6.0705E-5*TF-1.8442E-8*TF**2
        VISL=2.1019E-4-2.2755E-6*TF+1.0823E-8*TF**2
        VISV=1.18E-5+4E-8*TF
        SIG=0.0
      ELSEIF(FTYPE.EQ.'F23    ') THEN
        TLL=-40.
        TLU=10.
        IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
        CKL=7.4817E-2-7.547E-4*TF-1.4837E-6*TF**2
        CKV=1.7685E-2+2.1117E-4*TF+1.2942E-6*TF**2
        VISL=9.0309E-5-1.6701E-6*TF+4.2279E-9*TF**2
        VISV=1.5063E-5+1.3885E-7*TF+1.657E-9*TF**2
        SIG=0.0
      ELSEIF(FTYPE.EQ.'F113   ') THEN
        TLL=0.
        TLU=170.
        IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
        CKL=8.1947E-2-1.7689E-4*TF+1.3415E-8*TF**2
        CKV=7.7373E-3+4.3806E-5*TF+5.8518E-8*TF**2
        VISL=9.4573E-4-1.1889E-5*TF+7.0746E-8*TF**2-1.6326E-10*TF**3
        VISV=8.1603E-6+8.025E-8*TF-6.2726E-10*TF**2+2.3745E-12*TF**3
        SIG=0.0
      ELSEIF(FTYPE.EQ.'F114   ') THEN
        TLL=-40.
```

```
            TLU=115.
            IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
            CKL=7.0594E-2-2.389E-4*TF+4.0843E-9*TF**2
            CKV=8.1576E-5*TF+.00882409
            VISL=4.9155E-4-6.5554E-6*TF+4.3739E-8*TF**2-1.2737E-10*TF**3
            VISV=1.0578E-5+3.2039E-8*TF+1.2712E-10*TF**2
            SIG=0.0
         ELSEIF(FTYPE.EQ.'ENG    ') THEN
            TLL=0.
            TLU=156.
            IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
            VISL=3.8022-.31428*TF+.013304*TF**2-3.5893*TF**3
     #          +6.4967E-6*TF**4-7.9143E-8*TF**5+6.3585E-10*TF**6
     #          -3.2142E-12*TF**7+9.2318E-15*TF**8-1.146E-17*TF**9
            VISV=0.
            CKL=.147-7.18122E-5*TF-7.0708E-7*TF**2+3.6242E-9*TF**3
            CKV=0.
            SIG=0.
         ELSEIF(FTYPE.EQ.'ETHYLG') THEN
            TLL=0.
            TLU=100.
            IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
            VISL=.06442-.0041299*TF+1.4896E-4*TF**2-3.2665E-6*TF**3
     #          +4.1721E-8*TF**4-2.8171E-10*TF**5+7.4264E-13*TF**6
            VISV=0.
            CKL=.24194+3.205E-4*TF+2.4239E-6*TF**2-4.34E-9*TF**3
     #          -1.1914E-9*TF**4-8.8208E-12*TF**5
            CKV=0.
            SIG=0.
         ELSEIF(FTYPE.EQ.'GLYCRN') THEN
            TLL=0.
            TLU=46.
            IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
            VISL=10.457-.98243*TF+.03866*TF**2-7.1174E-4*TF**3
     #          +5.0052E-6*TF**4
            VISV=0.
            CKL=.282065+3.4417E-4*TF-1.0215E-5*TF**2+1.0936E-7*TF**3
            CKV=0.
            SIG=0.
         ELSEIF(FTYPE.EQ.'HG     ') THEN
            TLL=0.
            TLU=326.
            IF(TF.LT.TLL.OR.TF.GT.TLU) GOTO 100
            VISL=.0016815-6.15448E-6*TF+1.96029E-8*TF**2-2.4526E-11*TF**3
            VISV=0.
            CKL=8.1777+.013656*TF-6.49055E-6*TF**2
            CKV=0.
            SIG=0.
         ENDIF
         GOTO 5
100      ITR=1
5        RETURN
         END
C
      SUBROUTINE SIFLUID(CYCLE,LFTYPE,FGIVEN,SGIVEN,QL,ENTR,ENTH,VOL,
     # U,TEMP,PRESS,SL,HL,VL,UL,SV,HV,VV,UV)
      CHARACTER*6 LFTYPE
      CHARACTER*6 IFREON(9),ICARBN(12)
      CHARACTER*2 CYCLE
      COMMON/ERFLAG/ERFLAG
      DATA(IFREON(I),I=1,9)/'F11    ','F12    ','F13    ','F14    ',
     #  'F21    ','F22    ','F23    ','F113   ','F114   '/
```

```
           DATA(ICARBN(I),I=1,12)/'METH  ','ETH   ','PROP  ','BUT   ',
      #    'PENT  ','HEX   ','HEPT  ','OCT   ','ETHYL ','PROPYL',
      #    'ISOB  ','ISOP '/
           PARAMETER (M2=6)
           DO 100 I=1,9
           IF(LFTYPE.EQ.IFREON(I)) GOTO 400
  100 CONTINUE
           DO 200 I=1,12
           IF(LFTYPE.EQ.ICARBN(I)) GOTO 500
  200 CONTINUE
           IF(LFTYPE.EQ.'H2O   ') GOTO 300
    C      WRITE(M2,9000) LFTYPE
           VOL=-9999
           RETURN
  300 LN=10
           NS=0
           NP=0
           CALL SIWATER(CYCLE,FGIVEN,SGIVEN,LN,NS,NP,QL,ENTR,ENTH,VOL,U,
      #    TEMP,PRESS,SL,HL,VL,UL,SV,HV,VV,UV,NERROR)
           RETURN
  400 CALL SIFREON(CYCLE,FGIVEN,SGIVEN,LFTYPE,ENTH,ENTR,VOL,TEMP,PRESS,
      #    HV,SV,VV,HL,SL,VL,QL,NPRINT)
           U=0.0
           UL=0.0
           UV=0.0
           RETURN
  500 CONTINUE
           CALL SICARBON(CYCLE,FGIVEN,SGIVEN,LFTYPE,ENTH,ENTR,VOL,TEMP,
      #    PRESS,NP,SL,HL,VL,SV,HV,VV,QL)
           U=0.0
           UL=0.0
           UV=0.0
           RETURN
 9000 FORMAT(1H ,4X,'***ERROR IN FLUID*** THE FLUID ',A6,'CANNOT BE
EVAL
      #UATED')
           END
    C
      SUBROUTINE WATER(CYCLE,FGIVEN,SGIVEN,CALLIN,NSTAT1,NPRINA,QUAL1,
      #    ENTR1,ENTH1,VOL1,UINT1,TEMPF1,PRESS1,LSATS1,LSATH1,LSATV1,
      #    LSATU1,VSATS1,VSATH1,VSATV1,VSATU1,NERROR)
           IMPLICIT REAL(L)
           INTEGER CALLIN
           CHARACTER*2 CYCLE
           PARAMETER (M2=6,M1=5)
           COMMON/WATER1/VSATS,VSATH,VSATU,VSATV,LSATS,LSATH,LSATU,LSATV,
      #    TEMPK,TCRIT,PCRIT,TAUCRT,TGUESS,GAS,GAS1,CONVR,DPSDT,DGUESS,
      #    DENSIT,DPDRHO,TEMPF,PRESS,UINT,ENTH,VOL,ENTR,DHDT,DHDRHO,DPDT,
      #    SCAL,HCAL,DSDRHO,SJOULE,SKNOWN,ITERAT,PSAT,DENTOL,TTOLER,BTOLER,
      #    PCAL,QUAL,PKNOWN,DSDT
           COMMON/PRINTA/NPRINT,NSTATE
           DATA TTOLER,BTOLER,CONVR/1.001,0.999,0.4299229/
           DATA TCRIT,PCRIT,TAUCRT,GAS1,GAS/374.136,3203.6,1.544912,
      #    66.9366,0.46151/
           DATA ITERAT/2000/
           NSTATE=NSTAT1
           NPRINT=NPRINA
           TEMPF=TEMPF1
           ENTR=ENTR1
           ENTH=ENTH1
           PRESS=PRESS1
           LSATH=0.0
```

```
            LSATU=0.0
            LSATV=0.0
            LSATS=0.0
            VSATH=0.0
            VSATU=0.0
            VSATV=0.0
            VSATS=0.0
            NERROR=0.0
            IF(NPRINT.EQ.1) WRITE(M2,9000)
            IF(CYCLE.EQ.'TP')GOTO 1930
            IF(CYCLE.EQ.'TX'.OR.CYCLE.EQ.'PX')GOTO 1720
            IF(CYCLE.EQ.'PS')GOTO 1100
            IF(CYCLE.EQ.'PH')GOTO 1330
      C     WRITE(M2,9010)CYCLE,CALLIN
            NERROR=1
            RETURN
      C_____PRESSURE ENTROPY_____
      1100  SKNOWN=SGIVEN*1.8
            PKNOWN=FGIVEN
            PRESS=FGIVEN
            ENTR=SGIVEN
            IF(NPRINT.EQ.1) WRITE(M2,9050)
            IF(PRESS.LT.PCRIT) GOTO 1200
            TEMPK=500.0
               IF(ENTR.GT.1.0580) DENSIT=1.0E-05
            IF(ENTR.GT.1.0580) GOTO 1550
            DENSIT=0.96
            GOTO 1630
      1200  CALL TSATUR
            CALL VAPDEN(NSTAT1)
            IF(ENTR/SCAL.GT.TTOLER) GOTO 1550
            CALL LIQDEN(NSTAT1)
            IF(ENTR/SCAL.LT.BTOLER) GOTO 1630
            QUAL=(ENTR-LSATS)/(VSATS-LSATS)
            ENTH=(1.0-QUAL)*LSATH+QUAL*VSATH
            UINT=(1.0-QUAL)*LSATU+QUAL*VSATU
            VOL=(1.0-QUAL)*LSATV+QUAL*VSATV
            CALL PRINT
            GOTO 2200
      C_____PRESSURE ENTHALPY_____
      1330  PKNOWN=FGIVEN
            HKNOWN=SGIVEN
            PRESS=FGIVEN
            ENTH=SGIVEN
            IF(NPRINT.EQ.1) WRITE(M2,9060)
            IF(PRESS.LT.PCRIT) GOTO 1400
            TEMPK=500.0
            IF(ENTH.GT.902.5) DENSIT=1.0E-05
            IF(ENTH.GT.902.5) GOTO 1550
            DENSIT=0.96
            GOTO 1630
      1400  CALL TSATUR
            CALL VAPDEN(NSTAT1)
            IF(HKNOWN/HCAL.GT.TTOLER) GOTO 1550
            CALL LIQDEN(NSTAT1)
            IF(HKNOWN/HCAL.LT.BTOLER) GOTO 1630
            QUAL=(HKNOWN-LSATH)/(VSATH-LSATH)
            ENTR=(1.-QUAL)*LSATS + QUAL*VSATS
            UINT=(1.0-QUAL)*LSATU+QUAL*VSATU
            VOL=(1.0-QUAL)*LSATV + QUAL*VSATV
            CALL PRINT
            GOTO 2200
```

```
1550 DENTOL=1.0E-10
     IF(CYCLE.EQ.'PH') CALL PHFIND
     IF(CYCLE.EQ.'PS') CALL PSFIND
     ENTH=HCAL
     ENTR=SCAL
     IF(PRESS.GT.PCRIT) QUAL=-3.0
     IF(PRESS.LE.PCRIT) QUAL=2.0
     CALL PRINT
     GOTO 2200
1630 DENTOL=1.0E-05
     IF(CYCLE.EQ.'PH') GOTO 1680
     TEMPK=180.0*(5.4+9.630628*ENTR-2.640989*SQRT(ENTR)-0.10592*
    # ENTR**2)
     DENSIT=10.0/(62.4283*(0.12-.5276609*ENTR+.2878426*SQRT(ENTR)
    # +.4208526*ENTR**2))
     CALL PSFIND
     GOTO 1700
1680 TEMPK=1.8*(512.0+1.370531*ENTH+4.737845*SQRT(ENTH)+4.540232E-04*
    # ENTH**2)
     DENSIT=1.E+04/(62.4283*(149.2-.185626*ENTH+2.671239*SQRT(ENTH)+
    # .3508786E-03*ENTH**2))
     CALL PHFIND
1700 ENTH=HCAL
     ENTR=SCAL
     IF(PRESS.GT.PCRIT) QUAL=-3.0
     IF(PRESS.LE.PCRIT) QUAL=-2.0
     CALL PRINT
     GOTO 2200
1720 QUAL=SGIVEN
     IF(QUAL.GE.0.0) GOTO 1780
C    WRITE(M2,9020)
     QUAL=0.0
1780 IF(QUAL.LE.1.0) GOTO 1810
C    WRITE (M2,9030)
     QUAL=1.0
C_____PRESSURE QUALITY_____
1810 IF(CYCLE.EQ.'TX')GOTO 1870
     PRESS =FGIVEN
     PKNOWN=FGIVEN
     IF(NPRINT.EQ.1) WRITE(M2,9070)
     IF(PRESS.LE.PCRIT*0.99) GOTO 1890
     NERROR=1
C    WRITE(M2,9100)
     RETURN
1890 CALL TSATUR
     GOTO 2120
C_____TEMPERATURE-QUALITY _____
1870 TEMPF=FGIVEN
     IF(NPRINT.EQ.1) WRITE(M2,9080)
     IF(TEMPF.LE.705.0) GOTO 1900
     NERROR=1
C    WRITE(M2,9110)
     RETURN
1900 TEMPK=(TEMPF+459.67)/1.8
     CALL PSATUR
     PRESS=PSAT
     GOTO 2120
C_____PRESSURE TEMPERATURE_____
1930 TEMPF=FGIVEN
     PRESS=SGIVEN
     IF(NPRINT.EQ.1) WRITE(M2,9090)
     TEMPK=(TEMPF+459.67)/1.8
```

```
         IF(TEMPF.LT.705.0) GOTO 1960
         IF(PRESS.GT.PCRIT)GOTO 2080
         GOTO 2035
 1960 CALL PSATUR
         IF(PRESS/PSAT.GT.TTOLER.OR.PRESS/PSAT.LT.BTOLER)GOTO 2030
    c    WRITE(M2,9040)CALLIN,TEMPF,PRESS
         NERROR=1
         RETURN
 2030 IF(PRESS/PSAT.GT.TTOLER)GOTO 2080
 2035 QUAL=2.0
         DGUESS=1.E-05
         DENTOL=1.0E-10
         GOTO 2090
 2080 DGUESS=0.99
         DENTOL=1.E-07
         IF(TEMPF.LT.705.) QUAL=-2.0
         IF(TEMPF.GE.705.) QUAL=-3.0
 2090 CALL DFIND(NSTAT1)
         ENTH=HCAL
         ENTR=SCAL
         CALL PRINT
         GOTO 2200
 2120 IF(ABS(QUAL).LT.0.000001) GOTO 2150
         CALL VAPDEN(NSTAT1)
         IF(ABS(QUAL-1.0).LT.0.000001) GOTO 2160
 2150 CALL LIQDEN(NSTAT1)
 2160 ENTR=(1.0-QUAL)*LSATS+QUAL*VSATS
         UINT=(1.0-QUAL)*LSATU+QUAL*VSATU
         ENTH=(1.0-QUAL)*LSATH +QUAL*VSATH
         VOL=(1.0-QUAL)*LSATV+QUAL*VSATV
         CALL PRINT
 2200 TEMPF1=TEMPF
         VOL1=VOL
         ENTR1=ENTR
         ENTH1=ENTH
         UINT1=UINT
         PRESS1=PRESS
         QUAL1=QUAL
         LSATS1=LSATS
         LSATH1=LSATH
         LSATU1=LSATU
         LSATV1=LSATV
         VSATS1=VSATS
            VSATH1=VSATH
         VSATU1=VSATU
            VSATV1=VSATV
 9000 FORMAT(1H1,//,13X,'********    THERMODYNAMIC PROPERTIES OF WATER
    1 ********',////)
 9010 FORMAT(1H ,4X,'***ERROR*** CYCLE = ',A3,' CYCLE MUST EQUAL TP,
TX,
    1 PX, PS, PH, LAST CALL ON WATER CAME FROM LINE',I6,//,10X,'WATER
T
    2ERMINATED')
 9020 FORMAT(1H ,4X,'***ERROR*** A QUALITY OF < 0 IS NOT DEFINED,
ASSUME
    1D TO BE ZERO')
 9030 FORMAT(1H ,4X,'***ERROR*** A QUALITY OF > 1 IS NOT DEFINED,
ASSUME
    1D TO BE ONE')
 9040 FORMAT(1H ,4X,'***ERROR*** TEMPERATURE AND PRESSURE ARE NOT
INDEPE
    1NDENT UNDER THE SATURATION DOME',//,4X,'WATER TERMINATED, LAST
```

```
CAL
      2L CAME FROM LINE ',I6,/,10X,'TEMPERATURE = ',F15.5,10X,'PRESSURE
   =
      3 ',F15.5)
 9050 FORMAT(1H ,16X,'PRESSURE AND ENTROPY')
 9060 FORMAT(1H ,16X,'PRESSURE AND ENTHALPY')
 9070 FORMAT(1H ,16X,'PRESSURE AND QUALITY')
 9080 FORMAT(1H ,16X,'TEMPERATURE AND QUALITY')
 9090 FORMAT(1H ,16X,'TEMPERATURE AND PRESSURE')
 9100 FORMAT(1H ,4X,'***ERROR*** A SATURATION STATE DOES NOT EXIST FOR
P
      1RESSURES ABOVE THE CRITICAL PRESSURE(3203.6PSIA), WATER
TERMINATED
      2    ')
 9110 FORMAT(1H ,4X,'***ERROR*** A SATURATION STATE DOES NOT EXIST FOR
T
      1EMPERATURES ABOVE THE CRITICAL TEMPERATURE(750 DEG.F), WATER
TERMI
      2NATED')
      RETURN
      END
C     _____
      SUBROUTINE TSATUR
      IMPLICIT REAL(L)
      PARAMETER (M2=6)
      COMMON/WATER1/VSATS,VSATH,VSATU,VSATV,LSATS,LSATH,LSATU,LSATV,
     # TEMPK,TCRIT,PCRIT,TAUCRT,TGUESS,GAS,GAS1,CONVR,DPSDT,DGUESS,
     # DENSIT,DPDRHO,TEMPF,PRESS,UINT,ENTH,VOL,ENTR,DHDT,DHDRHO,DPDT,
     # SCAL,HCAL,DSDRHO,SJOULE,SKNOWN,ITERAT,PSAT,DENTOL,TTOLER,BTOLER,
     # PCAL,QUAL,PKNOWN,DSDT
      TSAT=340.0
      TEMPK=TSAT
      CALL PSATUR
      DO 2320 I=1,ITERAT
 2280 TEMPK=TSAT-(PSAT-PKNOWN)/DPSDT
      IF(TEMPK-273.15.GT.TCRIT) TEMPK=TCRIT+273.15
      CALL PSATUR
      IF(PSAT/PKNOWN.GT.BTOLER.AND.PSAT/PKNOWN.LT.TTOLER) GOTO 2330
      TSAT=TEMPK
 2320 CONTINUE
C     WRITE(M2,9000) ITERAT
 9000 FORMAT(1H ,'*** SATURATED TEMPERATURE SEARCH FAILED TO
     # CONVERGE IN',I5,' ITERATIONS, RESULTS MAY NO BE VALID***')
 2330 TSAT=TEMPK
      RETURN
      END
C     _____
      SUBROUTINE VAPDEN(NSTAT1)
      IMPLICIT REAL(L)
      COMMON/WATER1/VSATS,VSATH,VSATU,VSATV,LSATS,LSATH,LSATU,LSATV,
     1 TEMPK,TCRIT,PCRIT,TAUCRT,TGUESS,GAS,GAS1,CONVR,
     2 DPSDT,DGUESS,DENSIT,DPDRHO,TEMPF,PRESS,UINT,ENTH,VOL,
     3 ENTR,DHDT,DHDRHO,DPDT,SCAL,HCAL,DSDRHO,SJOULE,SKNOWN,
     4 ITERAT,PSAT,DENTOL,TTOLER,BTOLER,PCAL,QUAL,PKNOWN,DSDT
      DGUESS=1.E-06
      DENTOL=1.E-12
      CALL DFIND(NSTAT1)
      VSATV=VOL
      VSATU=UINT
      VSATS=SCAL
      VSATH=HCAL
      RETURN
```

```
       END
C   _____
       SUBROUTINE LIQDEN(NSTAT1)
C   SET UP SEARCH FOR SATURATED LIQUID
       IMPLICIT REAL (L)
       COMMON/WATER1/VSATS,VSATH,VSATU,VSATV,LSATS,LSATH,LSATU,LSATV,
      1 TEMPK,TCRIT,PCRIT,TAUCRT,TGUESS,GAS,GAS1,CONVR,
      2 DPSDT,DGUESS,DENSIT,DPDRHO,TEMPF,PRESS,UINT,ENTH,VOL,
      3 ENTR,DHDT,DHDRHO,DPDT,SCAL,HCAL,DSDRHO,SJOULE,SKNOWN,
      4 ITERAT,PSAT,DENTOL,TTOLER,BTOLER,PCAL,QUAL,PKNOWN,DSDT
       DGUESS=0.96
       DENTOL=1.0E-07
       CALL DFIND(NSTAT1)
       LSATV=VOL
       LSATU=UINT
       LSATS=SCAL
       LSATH=HCAL
       RETURN
       END
C   _____
       SUBROUTINE PRINT
C   PRINT
       IMPLICIT REAL (L)
       COMMON/WATER1/VSATS,VSATH,VSATU,VSATV,LSATS,LSATH,LSATU,LSATV,
      1 TEMPK,TCRIT,PCRIT,TAUCRT,TGUESS,GAS,GAS1,CONVR,
      2 DPSDT,DGUESS,DENSIT,DPDRHO,TEMPF,PRESS,UINT,ENTH,VOL,
      3 ENTR,DHDT,DHDRHO,DPDT,SCAL,HCAL,DSDRHO,SJOULE,SKNOWN,
      4 ITERAT,PSAT,DENTOL,TTOLER,BTOLER,PCAL,QUAL,PKNOWN,DSDT
       COMMON/PRINTA/NPRINT,NSTATE
       PARAMETER (M2=6)
       TEMPF=TEMPK*1.8-459.67
       IF(NPRINT.EQ.0) RETURN
C      WRITE(M2,9040) NSTATE
C      WRITE(M2,9050) TEMPF,PRESS
       IF(QUAL.LE.1.0.AND.QUAL.GE.0.0) GOTO 3280
C      IF(QUAL.GT.1.0) WRITE(M2,9060)
C      IF(QUAL.LT.0.0.AND.QUAL.GT.-2.5) WRITE(M2,9070)
C      IF(QUAL.LT.-2.5) WRITE(M2,9030)
       GOTO 3370
 3280  continue
C      WRITE(M2,9080) QUAL
C      WRITE(M2,9130)
C      WRITE(M2,9090) VSATU,LSATU
C      WRITE(M2,9100) VSATH,LSATH
C      WRITE(M2,9110) VSATS,LSATS
C      WRITE(M2,9120) VSATV,LSATV
 3370  continue
C      WRITE(M2,9140)
C      WRITE(M2,9090) UINT
C      WRITE(M2,9100) ENTH
C      WRITE(M2,9110) ENTR
C      WRITE(M2,9120) VOL
 9030  FORMAT(1H ,16X,'CRITICAL SOLUTION',//)
 9040  FORMAT(1H ,16X,'PROPERTIES OF WATER AT STATE ',I4,/)
 9050  FORMAT(1H ,16X,'TEMPERATURE = ',F7.2,' DEG.F',/,
      1 17X,'PRESSURE    = ',F10.5,' PSIA')
 9060  FORMAT(1H ,16X,'SUPERHEATED VAPOR')
 9070  FORMAT(1H ,16X,'COMPRESSED LIQUID')
 9080  FORMAT(1H ,16X,'SATURATED LIQUID-VAPOR EQUILIBRIUM',/,17X,
      1 'QUALITY = ',F6.4)
 9090  FORMAT(1H ,16X,'INTERNAL ENERGY (BTU/LBM)',5X,F9.3,8X,F9.3)
 9100  FORMAT(1H ,16X,'ENTHALPY',8X,'(BTU/LBM)',5X,F9.3,8X,F9.3)
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9120 FORMAT(1H ,16X,'SPECIFIC VOLUME (CU.FT/LBM )',2X,F9.4,8X,F9.4)
9110 FORMAT(1H ,16X,'ENTROPY',9X,'(BTU/LBM-R)',3X,F9.6,8X,F9.6)
9130 FORMAT(1H ,16X,'SATURATED',8X,'SATURATED',/,47X,'VAPOR',12X,
    1 'LIQUID',/,17X,60('#'))
9140 FORMAT(1H ,/)
     RETURN
     END
C_____
     SUBROUTINE PHFIND
C NEWTON-RAPHSON ITERATION TO FIND DENSITY AND TEMPERATURE GIVEN
C   PRESSURE AND ENTHALPY FOR SUPERHEATED VAPOR AND COMPRESSED LIQUID
     IMPLICIT REAL (L)
     PARAMETER (M2=6)
     COMMON/WATER1/VSATS,VSATH,VSATU,VSATV,LSATS,LSATH,LSATU,LSATV,
    1 TEMPK,TCRIT,PCRIT,TAUCRT,TGUESS,GAS,GAS1,CONVR,
    2 DPSDT,DGUESS,DENSIT,DPDRHO,TEMPF,PRESS,UINT,ENTH,VOL,
    3 ENTR,DHDT,DHDRHO,DPDT,SCAL,HCAL,DSDRHO,SJOULE,SKNOWN,
    4 ITERAT,PSAT,DENTOL,TTOLER,BTOLER,PCAL,QUAL,PKNOWN,DSDT
     REAL JACOB
     TT=1.001
     BT=.999
     DENT=1.0E-11
     DLAST=DENSIT
     TLAST=TEMPK
     CALL PROPER
     DO 3600 I=1,ITERAT
3470 JACOB=DPDRHO*DHDT-DHDRHO*DPDT
     DENSIT=DLAST-((PCAL-PRESS  )*DHDT-(HCAL-ENTH)*DPDT)/JACOB
     IF(DENSIT.LE.1.0E-10) DENSIT=DLAST/10.0
     TEMPK=TLAST-((HCAL-ENTH)*DPDRHO-(PCAL-PRESS)*DHDRHO)/JACOB
     IF (TEMPK.LE.0.0) TEMPK=300.0
     CALL PROPER
     IF(PCAL/PRESS .LT.TT.AND.PCAL/PRESS.GT.BT.AND.
    1   HCAL/ENTH.LT.TT.AND.HCAL/ENTH.GT.BT) RETURN
     IF(ABS(DLAST-DENSIT).LT.DENT.AND.
    1   ABS(TLAST-TEMPK).LT.1.0E-04)   RETURN
     DLAST=DENSIT
     TLAST=TEMPK
3600 CONTINUE
c    WRITE(M2,9000) ITERAT
9000 FORMAT('  ***TEMPERATURE-DENSITY SEARCH,GIVEN PRESSURE & ENTHALPY,
    1FAILED TO CONVERGE IN ',I5,' ITERATIONS, RESULTS MAY NOT BE
    2VALID')
     RETURN
     END
C  _____
     SUBROUTINE PSFIND
C NEWTON-RAPHSON ITERATIN TO FIND DENSITY AND TEMPERATURE
C GIVEN PRESSURE
C AND ENTROPY FOR SUPERHEATED VAPOR AND OCMPRESSED LIQUID
     IMPLICIT REAL (L)
     PARAMETER (M2=6)
     COMMON/WATER1/VSATS,VSATH,VSATU,VSATV,LSATS,LSATH,LSATU,LSATV,
    1 TEMPK,TCRIT,PCRIT,TAUCRT,TGUESS,GAS,GAS1,CONVR,
    2 DPSDT,DGUESS,DENSIT,DPDRHO,TEMPF,PRESS,UINT,ENTH,VOL,
    3 ENTR,DHDT,DHDRHO,DPDT,SCAL,HCAL,DSDRHO,SJOULE,SKNOWN,
    4 ITERAT,PSAT,DENTOL,TTOLER,BTOLER,PCAL,QUAL,PKNOWN,DSDT
     REAL JACOB
     DLAST=DENSIT
     TLAST=TEMPK
     CALL PROPER
     DO 4000 I=1,ITERAT
```

```
3790 JACOB=DPDRHO*DSDT-DSDRHO*DPDT
     DENSIT=DLAST-((PCAL-PRESS)*DSDT-(SJOULE-SKNOWN)*DPDT)/JACOB
     IF(DENSIT.LE.1.E-10) DENSIT=DLAST/10.0
     TEMPK=TLAST-((SJOULE-SKNOWN)*DPDRHO-(PCAL-PRESS)*DSDRHO)/JACOB
     IF(TEMPK.LE.0.0) TEMPK=300.0
     CALL PROPER
     IF(PCAL/PRESS.LT.TTOLER.AND.PCAL/PRESS.GT.BTOLER.AND.SCAL/
    1ENTR.LT.TTOLER.AND.SCAL/ENTR.GT.BTOLER) RETURN
     IF(ABS(DLAST-DENSIT).LT.DENTOL.AND.ABS(TLAST-TEMPK).LT.1.0E-04)
    1                                                          RETURN
     DLAST=DENSIT
     TLAST=TEMPK
4000 CONTINUE
C    WRITE(M2,9000) ITERAT
9000 FORMAT(' ***TEMPRATURE-DENSITY SEARCH GIVEN PRESSURE AND ENTROPY
    1FAILED TO CONVERGE IN ',I5,' ITERATIONS, RESULTS MAY NO BE VALID'
    2 )
     RETURN
     END
C
     SUBROUTINE PSATUR
C    COMPUTES SATURATION GIVEN SATURATION TEMPERATURE
     IMPLICIT REAL (L)
     COMMON/WATER1/VSATS,VSATH,VSATU,VSATV,LSATS,LSATH,LSATU,LSATV,
    1 TEMPK,TCRIT,PCRIT,TAUCRT,TGUESS,GAS,GAS1,CONVR,
    2 DPSDT,DGUESS,DENSIT,DPDRHO,TEMPF,PRESS,UINT,ENTH,VOL,
    3 ENTR,DHDT,DHDRHO,DPDT,SCAL,HCAL,DSDRHO,SJOULE,SKNOWN,
    4 ITERAT,PSAT,DENTOL,TTOLER,BTOLER,PCAL,QUAL,PKNOWN,DSDT
     DIMENSION F(8)
     DATA(F(I),I=1,8)/-741.9242,-29.721,-11.55286,-0.8685635,
    #   0.1094098,0.439993,0.2520658,0.05218684/
     TAU=1000.0/TEMPK
     TEMPC=TEMPK-273.15
     SUM1=0.0
     SUM2=0.0
     DO 2420 I=1,8
     SUM1=SUM1+F(I)*(0.65-0.01*TEMPC)**(I-1)
     SUM2=SUM2+F(I)*(I-1)*0.01*(0.65-0.01*TEMPC)**(I-2)
2420 CONTINUE
     PSAT=EXP(TAU*1.0E-05*(TCRIT-TEMPC)*SUM1)*PCRIT
     DPSDT=PSAT/100.0*(((TEMPC-TCRIT)/TEMPK**2-1.0/TEMPK)*SUM1
    #  -(TCRIT/TEMPK-TEMPC/TEMPK)*SUM2)
     RETURN
     END
C
     SUBROUTINE DFIND(NSTAT1)
C    NEWTON RAPHSON METHOD TO LOCATE DENSITY GIVEN PRESSURE
C    AND TEMPERATURE
     IMPLICIT REAL (L)
     PARAMETER (M2=6)
     COMMON/WATER1/VSATS,VSATH,VSATU,VSATV,LSATS,LSATH,LSATU,LSATV,
    1 TEMPK,TCRIT,PCRIT,TAUCRT,TGUESS,GAS,GAS1,CONVR,
    2 DPSDT,DGUESS,DENSIT,DPDRHO,TEMPF,PRESS,UINT,ENTH,VOL,
    3 ENTR,DHDT,DHDRHO,DPDT,SCAL,HCAL,DSDRHO,SJOULE,SKNOWN,
    4 ITERAT,PSAT,DENTOL,TTOLER,BTOLER,PCAL,QUAL,PKNOWN,DSDT
     DENSIT=DGUESS
     LASTD2=DGUESS
     CALL PROPER
     DO 2560 I=1,ITERAT
2510 DENSIT=LASTD2-(PCAL-PRESS)/DPDRHO
     IF(DENSIT.LE.1.E-10) DENSIT=LASTD2/10.0
     CALL PROPER
```

```
       IF(PCAL/PRESS.GT.BTOLER.AND.PCAL/PRESS.LT.TTOLER.OR.
     # ABS(LASTD2-DENSIT).LT.DENTOL) RETURN
       LASTD2=DENSIT
 2560 CONTINUE
C      WRITE(M2,9000) ITERAT,PRESS,PCAL
 9000 FORMAT(' *** DENSITY SEARCH FAILED TO CONVERGE IN',I5,'
     1 ITERATIONS, RESULTS MAY NOT BE VALID***',/,
     2' DESIRED PRESSURE=',F10.3,' CALCULATED PRESSURE=',F10.3)
C      WRITE(M2,9001) NSTAT1
 9001 FORMAT(1H ,'STATE NUMBER',I3)
       RETURN
       END
C      _____
           SUBROUTINE PROPER
C   COMPUTES PROPERTIES AND THEIR DERIVATIVES
       IMPLICIT REAL (L)
       COMMON/WATER1/VSATS,VSATH,VSATU,VSATV,LSATS,LSATH,LSATU,LSATV,
     1 TEMPK,TCRIT,PCRIT,TAUCRT,TGUESS,GAS,GAS1,CONVR,
     2 DPSDT,DGUESS,DENSIT,DPDRHO,TEMPF,PRESS,UINT,ENTH,VOL,
     3 ENTR,DHDT,DHDRHO,DPDT,SCAL,HCAL,DSDRHO,SJOULE,SKNOWN,
     4 ITERAT,PSAT,DENTOL,TTOLER,BTOLER,PCAL,QUAL,PKNOWN,DSDT
       DIMENSION A(10,7),C(8)
       DATA((A(I,J),J=1,7),I=1,10)/29.492937,-5.198586,6.8335354,
     # -0.1564104,-6.3972405,-3.9661401,-0.69048554,-132.13917,
     # 7.7779182,-26.149751,-0.72546108,26.409282,15.453061,
     # 2.7407416,274.64632,-33.301902,65.326396,-9.2734289,
     # -47.740374,-29.142470,-5.1028070,-360.93828,-16.254622,
     # -26.181978,4.312584,56.32313,29.568796,3.9636085,342.18431,
     # -177.31074,0.0,0.0,0.0,0.0,0.0,-244.50042,127.48742,
     # 0.0,0.0,0.0,0.0,0.0,155.18535,137.46153,0.0,0.0,0.0,
     # 0.0,0.0,5.9728487,155.97836,0.0,0.0,0.0,0.0,0.0,
     # -410.30848,337.31180,-137.46618,6.7874983,136.87317,
     # 79.84797,13.041253,-416.0586,-209.88866,-733.96848,
     # 10.401717,645.8188,399.1757,71.531353 /
       DATA(C(I),I=1,8) /1857.065,3229.12,-419.465,36.6649,-20.5516,
     # 4.85233,46.0,-1011.249/
       VOL=1.0/(62.4283*DENSIT)
       TAU=1000.0/TEMPK
       Z3SUM=0.0
       Z4SUM=0.0
       Z5SUM=0.0
       D2QDTA=0.0
       W2SUM=0.0
       Z9SUM=0.0
       DO 2890 J=1,7
       IF(J.EQ.1) GOTO 2680
       DCON=1.0
       TAUCON=2.5
       GOTO 2700
 2680 DCON=0.634
       TAUCON=TAUCRT
 2700 CONTINUE
       ZSUM=0.0
       Z2SUM=0.0
       WSUM=0.0
       DO 2740 I=1,8
       ZSUM=ZSUM+A(I,J)*(DENSIT-DCON)**(I-1)
       Z2SUM=Z2SUM+A(I,J)*(I-1)*(DENSIT-DCON)**(I-2)
       WSUM=WSUM+A(I,J)*(I-1)*(I-2)*(DENSIT-DCON)**(I-3)
 2740 CONTINUE
       Z1SUM=0.0
       DO 2780 I=9,10
```

```
      Z1SUM=Z1SUM+A(I,J)*DENSIT**(I-9)
2780 CONTINUE
      Z1SUM=Z1SUM*EXP(-4.8*DENSIT)
      W1SUM=Z1SUM*23.04
      Z3SUM=Z3SUM+(TAU-TAUCON)**(J-2)*(ZSUM+Z1SUM)
      Z4SUM=Z4SUM+(TAU-TAUCON)**(J-2)*(Z2SUM-4.8*Z1SUM+EXP(-4.8*DENSIT)
     1 *A(10,J))
      Z5SUM=Z5SUM+((TAU-TAUCON)**(J-2)+(TAU-TAUCRT)*(J-2)*(TAU-TAUCON)
     1 **(J-3))*(ZSUM+Z1SUM)
      Z9SUM=Z9SUM+(J-2)*(TAU-TAUCON)**(J-3)*(Z2SUM-4.8*Z1SUM+
     1 EXP(-4.8*DENSIT)*A(10,J))*(TAU-TAUCRT)
      W2SUM=W2SUM+(TAU-TAUCON)**(J-2)*(WSUM+W1SUM-9.6*EXP(-4.8*DENSIT)
     1 *A(10,J))
      D2QDTA=D2QDTA+((TAU-TAUCRT)*(J-2)*(J-3)*(TAU-TAUCON)**(J-4)+
     1 2.0*(J-2)*(TAU-TAUCON)**(J-3))*(ZSUM+Z1SUM)
2890 CONTINUE
      Q=(TAU-TAUCRT)*Z3SUM
      DQDRHO=(TAU-TAUCRT)*Z4SUM
      DQDTAU=Z5SUM
      Z6SUM=0.0
      Z7SUM=0.0
      Z8SUM=0.0
      X7SUM=0.0
      DO 2990 I=1,6
      X7SUM=X7SUM+(2-I)*(1-I)*C(I)/TAU**I
      Z6SUM=Z6SUM+(2-I)*C(I)/TAU**(I-1)
      Z7SUM=C(I)*(I-1)*TAU**(2-I)/1000.0+Z7SUM
      Z8SUM=Z8SUM+C(I)*(I-1)*(I-2)*TAU**(3-I)
2990 CONTINUE
      D2CDT2=Z8SUM*1.0E-06-C(7)/TEMPK**2+C(8)/(1000.0*TEMPK)
      D2QDD2=(TAU-TAUCRT)*W2SUM
      D2CTDT=X7SUM-C(7)/TAU+C(8)/TAU**2
      DCTDT=Z6SUM+C(7)*(LOG(TEMPK)-1.0)-C(8)/TAU
      DCDT=Z7SUM+C(7)/TEMPK+C(8)/1000.0*(LOG(TEMPK)+1.0)
      PCAL=DENSIT*GAS1*TEMPK*(1.0+Q*DENSIT+DENSIT**2*DQDRHO)
      UINT=CONVR*(1000.0*GAS*DENSIT*DQDTAU+DCTDT)
      SCAL=CONVR*(-GAS*(LOG(DENSIT)+DENSIT*Q-DENSIT*TAU*DQDTAU)
     1 -DCDT)/1.8
      SJOULE=SCAL*1.8
      HCAL=CONVR*(GAS*TEMPK*(DENSIT*TAU*DQDTAU+1.0+DENSIT*Q+
     1 DENSIT**2*DQDRHO)+DCTDT)
      DQDDDT=(Z9SUM+Z4SUM)*(-TAU/TEMPK)
      DPDRHO=GAS1*TEMPK*(1.0+2.0*Q*DENSIT+4.0*DENSIT**2*DQDRHO+
     1 DENSIT**3*D2QDD2)
      DHDT=CONVR*(GAS*(1.0+DENSIT*Q+DENSIT**2*DQDRHO-TAU*DENSIT*DQDTAU
     1 -DENSIT*TAU**2*D2QDTA+TEMPK*DENSIT**2*DQDDDT)-TAU/TEMPK*D2CTDT)
      DHDRHO=GAS*CONVR*TEMPK*(TAU*DQDTAU-TEMPK*DENSIT*DQDDDT+Q
     1 +3.0*DENSIT*DQDRHO+DENSIT**2*D2QDD2)
      DPDT=DENSIT*GAS1*(1.0+DENSIT*Q+DENSIT**2*DQDRHO+TEMPK*DENSIT*
     1 (-TAU/TEMPK*DQDTAU+DENSIT*DQDDDT))
      DSDRHO=-CONVR*GAS*(1.0/DENSIT+Q+DENSIT*DQDRHO-TAU*DQDTAU
     1 +DENSIT*TEMPK*DQDDDT)
      DSDT=-CONVR*(GAS*TAU**2/TEMPK*DENSIT*D2QDTA+D2CDT2)/1.8
      RETURN
      END
C     _____
      SUBROUTINE SIWATER(CYCLE,FGIVEN,SGIVEN,CALLIN,NSTAT1,NPRINA,
     #QUAL1,ENTR1,ENTH1,VOL1,UINT1,TEMPF1,PRESS1,SATLS1,SATLH1,
     #SATLV1,SATLU1,VSATS1,VSATH1,VSATV1,VSATU1,NERROR)
      INTEGER CALLIN
      CHARACTER*2 CYCLE
      IF(CYCLE.EQ.'TP') THEN
```

```
        FGIVEN=FGIVEN*1.8+32.
        SGIVEN=.145037743897283*SGIVEN
        ELSEIF(CYCLE.EQ.'TX') THEN
        FGIVEN=FGIVEN*1.8+32.
        ELSEIF(CYCLE.EQ.'PS') THEN
        FGIVEN=.1450237743897283*FGIVEN
        SGIVEN=SGIVEN/4.1868
        ELSEIF(CYCLE.EQ.'PH') THEN
        FGIVEN=.145037743897283*FGIVEN
        SGIVEN=SGIVEN/2.326
        ELSEIF(CYCLE.EQ.'PX') THEN
        FGIVEN=FGIVEN*.145037743897283
        ELSE
        PRINT*,'WRONG CYCLE VALUE IS GIVEN'
        RETURN
        ENDIF
        CALLIN=10
        NSTAT1=0
        NPRINA=0
10      CALL WATER(CYCLE,FGIVEN,SGIVEN,CALLIN,NSTAT1,NPRINA,QUAL1,
     #     ENTR1,ENTH1,VOL1,UINT1,TEMPF1,PRESS1,SATLS1,SATLH1,SATLV1,
     #     SATLU1,VSATS1,VSATH1,VSATV1,VSATU1,NERROR)
        ENTR1=ENTR1*4.1868
        ENTH1=ENTH1*2.326
        VOL1=VOL1*0.0624219
        UINT1=UINT1*2.326
        TEMPF1=(TEMPF1-32.)/1.8
        PRESS1=PRESS1/.145037743897283
        SATLS1=SATLS1*4.1868
        SATLH1=SATLH1*2.326
        SATLV1=SATLV1*0.0624219
        SATLU1=SATLU1*2.326
        VSATS1=VSATS1*4.1868
        VSATH1=VSATH1*2.326
        VSATV1=VSATV1*0.0624219
        VSATU1=VSATU1*2.326
        RETURN
        END
        SUBROUTINE SICARBON(CYCLE,FGIVEN,SGIVEN,LFTYPE,H,S,V,TR,P,NPRIN,
     #   SL,HL,VL,SV,HV,VV,QUAL)
        IMPLICIT REAL(L)
        INTEGER CALLIN
        CHARACTER CYCLE*2,LFTYPE*6
        COMMON/ERFLAG/ERFLAG
        IF(CYCLE.EQ.'TP') THEN
        FGIVEN=FGIVEN*1.8+32.
        SGIVEN=.1450377*SGIVEN
        ELSEIF(CYCLE.EQ.'TX') THEN
        FGIVEN=FGIVEN*1.8+32.
        ELSEIF(CYCLE.EQ.'PS') THEN
        FGIVEN=.1450377*FGIVEN
        SGIVEN=SGIVEN/4.1868
        ELSEIF(CYCLE.EQ.'PH') THEN
        FGIVEN=.1450377*FGIVEN
        SGIVEN=SGIVEN/2.326
        ELSEIF(CYCLE.EQ.'PX') THEN
        FGIVEN=FGIVEN*.1450377
        ELSEIF(CYCLE.EQ.'TV') THEN
        FGIVEN=FGIVEN*1.8+32.
        SGIVEN=SGIVEN*16.01846
        ELSE
        PRINT*,'WRONG CYCLE VALUE IS GIVEN'
```

```
        RETURN
        ENDIF
        CALL CARBON(CYCLE,FGIVEN,SGIVEN,LFTYPE,H,S,V,TR,P,NPRIN,
     #  SL,HL,VL,SV,HV,VV,QUAL)
        S=S*4.1868
        H=H*2.326
        V=V*0.0624219
        TR=(TR-32.)/1.8
        P=P/.1450377
        SL=SL*4.1868
        HL=HL*2.326
        VL=VL/16.01846
        SV=SV*4.1868
        HV=HV*2.326
        VV=VV/16.01846
        RETURN
        END
C
        SUBROUTINE CARBON(CYCLE,FGIVEN,SGIVEN,LFTYPE,H,S,V,TR,P,NPRIN,
     #  SL,HL,VL,SV,HV,VV,QUAL)
        CHARACTER LFTYPE*6,CYCLE*2
        COMMON/CAR1/C(11),CS(6),CH(6),WM,R,CONVR,LIMIT,ABST,TTOLER,BTOLER
        COMMON/ERFLAG/ERFLAG
        PARAMETER (M2=6)
        DIMENSION XISOB(27),XISOP(27),XMETH(27),ETH(27),PROP(27),
     1PENT(27),HEX(27),BUT(27),HEPT(27),OCT(27),ETHYL(27),PROPYL(27)
        DATA ABST,TTOLER,BTOLER,LIMIT,R/459.67,1.001,0.999,100,10.7335/
        DATA CONVR/0.185057/
        DATA(XISOB(I),I=1,27)/479907.0E-01,37264.0,8.58663,1.87890,
     #406763.0E05,101413.0E05,216863.0E02,853176.0E06,840860.0E08,
     #4.23987,7.11486,0.86401,9.079E-04,-2.073E-07,0.885E-10,
     #-0.241E-13,0.0,-776.11,6.872E-02,3.071E-04,0.0,0.0,0.0,
     #529.06,274.96,0.2373,58.12/
        DATA(PENT(I),I=1,27)/162185.0,51108.2,16.6070,2.44417,
     #135286.0E06,223931.0E05,388521.0E02,101769.0E07,
     #390860.0E08,7.06702,11.8593,
     #0.9179,1.511E-04,14.048E-07,-13.785E-10,4.560E-13,0.0,
     #-688.09,22.267E-02,-0.89E-04,5.018E-07,-3.048E-10,
     #0.641E-13,489.51,385.42,0.2007,72.146/
        DATA(PROP(I),I=1,27)/40066.4,18634.7,5.46248,
     #0.964762,274461.0E05,
     #796178.0E04,150520.0E02,453708.0E06,256053.0E08,2.01402,4.56182,
     #0.9353,26.158E-04,-56.478E-07,85.177E-10,-63.595E-13,18.451E-16,
     #-804.84,25.477E-02,-1.602E-04,5.160E-07,-2.110E-10,0.0,617.400,
     #206.13,0.3021,44.094/
        DATA(XMETH(I),I=1,27)/2574.89,7520.29,0.925404,0.723251,
     #437222.0E03,271092.0E03,47489.1,107737.0E05,301122.0E05,0.468828,
     #1.4860,1.7491,68.131E-04,-167.165E-07,244.251E-10,-180.176E-13,
     #52.320E-16,-1798.16,53.978E-02,-1.345E-04,0.676E-07,1.966E-10,
     #-1.037E-13,673.1,-116.43,0.62747,16.042/
        DATA(ETH(I),I=1,27)/22404.5,13439.3,3.11206,0.826059,681826.0E04,
     #295195.0E04,702189.0,257477.0E06,146819.0E08,0.90681,2.99656,
     #1.3021,23.761E-04,-32.627E-07,28.695E-10,-9.485E-13,0.0,-993.32,
     #30.668E-02,-1.427E-04,4.203E-07,-1.567E-10,0.0,709.8,90.03,
     #0.4218,30.068/
        DATA(PROPYL(I),I=1,27)/81880.4,6051.36,7.64114,0.114457,
     #29141.0E05,974762.0E04,54193.5E02,705921.0E06,341250.0E08,
     #1.36532,4.07919,1.2501,7.946E-04,-1.155E-07,-0.025E-10,0.054E-13,
     #0.0,376.86,9.868E-02,2.347E-04,0.295E-07,-0.196E-10,0.0,670.27,
     #197.4,0.3449,42.08/
        DATA(HEX(I),I=1,27)/434517.0,45333.1,29.4983,2.66233,318412.0E06,
     #526067.0E05,327460.0E02,552158.0E07,626433.0E09,9.70230,14.8720,
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#1.3746,-17.514E-04,35.508E-07,-21.907E-10,4.769E-13,0.0,
#-618.38,.240E-02,4.148E-04,-.614E-07,
#0.0,0.0,439.4,453.45,0.1696,86.172/
 DATA(XISOP(I),I=1,27)/204344.0,35742.0,19.8384,
#1.27752,129083.0E06
#,228430.0E05,349220.0E02,142115.0E07,241326.0E08,6.16154,11.7384,
#.7737,9.412E-04,-3.298E-07,2.306E-10,-.953E-13,.129E-16,
#-709.28,7.482E-02,2.545E-04,.857E-07,
#-0.464E-10,0.0,483.5,369.0,0.2027,72.146/
 DATA(BUT(I),I=1,27)/71181.8,32544.7,9.14066,1.56588,700044.0E05
#,137436.0E05,364238.0E02,333159.0E06,230902.0E07,4.00985,7.54122,
#0.9008,10.06E-04,-3.006E-07,0.846E-10,0.0,0.0,-739.77,22.389E-02,
#-0.601E-04,3.93E-07,-1.594E-10,0.0,551.1,305.67,0.2448,58.12/
 DATA(HEPT(I),I=1,27)/359087.0,77826.9,27.4415,
#3.60493,374876.0E06,
#615662.0E05,8351150.0,777123.0E07,636251.0E07,21.8782,24.7604,
#1.3170,-17.863E-04,36.047E-07,-22.278E-10,4.856E-13,0.0,-596.40,
#0.549E-02,3.989E-04,-0.587E-07,0.0,0.0,396.8,
#512.85,0.1465,100.198/
 DATA(OCT(I),I=1 ,27)/131646.0,81690.6,10.5907,
#4.86965,642053.0E06,
#996546.0E05,185906.0E03,790575.0E07,346419.0E08,34.5124,21.9888,
#.2641,-17.734E-04,35.827E-07,-22.131E-10,4.823E-13,0.0,-577.59,
#0.612E-02,4.094E-04,-0.605E-07,0.0,0.0,364.
#4,563.79,0.1284,114.224/
 DATA(ETHYL(I),I=1,27)/15978.1,12133.9,
#2.62914,0.747945,409725.0E04
#,163203.0E04,903550.0,517563.0E05,161706.0E05,0.589158,2.27971,
#1.3982,23.551E-04,-34.268E-07,30.347E-10,-10.071E-13,0.0,928.25,
#32.949E-02,-2.477E-04,4.768E-07,-1.711E-10,0.0,
#742.0,49.82,0.5035,28.05/
 ERFLAG=2.
 IF(LFTYPE.EQ.'ISOB  ') GOTO 10
 IF(LFTYPE.EQ.'PENT  ') GOTO 20
 IF(LFTYPE.EQ.'ISOP  ') GOTO 30
 IF(LFTYPE.EQ.'METH  ') GOTO 40
 IF(LFTYPE.EQ.'ETH   ') GOTO 50
 IF(LFTYPE.EQ.'PROP  ') GOTO 60
 IF(LFTYPE.EQ.'HEX   ') GOTO 70
 IF(LFTYPE.EQ.'BUT   ') GOTO 80
 IF(LFTYPE.EQ.'HEPT  ') GOTO 90
 IF(LFTYPE.EQ.'OCT   ') GOTO 100
 IF(LFTYPE.EQ.'ETHYL ') GOTO 110
 IF(LFTYPE.EQ.'PROPYL') GOTO 120
c    WRITE(M2,9050)lftype
     RETURN
 10 CALL SETUP(XISOB,PCRIT,TCRIT,DCRIT)
     GOTO 180
 20 CALL SETUP(PENT,PCRIT,TCRIT,DCRIT)
     GOTO 180
 30 CALL SETUP(XISOP,PCRIT,TCRIT,DCRIT)
     GOTO 180
 40 CALL SETUP(XMETH,PCRIT,TCRIT,DCRIT)
     GOTO 180
 50 CALL SETUP(ETH,PCRIT,TCRIT,DCRIT)
     GOTO 180
 60 CALL SETUP(PROP,PCRIT,TCRIT,DCRIT)
     GOTO 180
 70 CALL SETUP(HEX,PCRIT,TCRIT,DCRIT)
     GOTO 180
 80 CALL SETUP(BUT,PCRIT,TCRIT,DCRIT)
     GOTO 180
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   90 CALL SETUP(HEPT,PCRIT,TCRIT,DCRIT)
      GOTO 180
  100 CALL SETUP(OCT,PCRIT,TCRIT,DCRIT)
      GOTO 180
  110 CALL SETUP(ETHYL,PCRIT,TCRIT,DCRIT)
      GOTO 180
  120 CALL SETUP(PROPYL,PCRIT,TCRIT,DCRIT)
  180 IF(CYCLE.EQ.'TP')GOTO 200
      IF(CYCLE.EQ.'TX') GOTO 400
      IF(CYCLE.EQ.'PX') GOTO 600
      IF(CYCLE.EQ.'PS') GOTO 800
      IF(CYCLE.EQ.'PH') GOTO 1000
      IF(CYCLE.EQ.'TV') GOTO 1200
C     WRITE(M2,9000) CYCLE
      RETURN
  200 T=FGIVEN
      P=SGIVEN
      TR=T+ABST
      IF(T.GE.TCRIT) GOTO 220
      TCRITR=TCRIT+ABST
      CALL PRESAT(TR,PSAT,DL,DV,DCRIT,TCRITR,LFTYPE)
      IF(P/PSAT.GT.TTOLER.OR.P/PSAT.LT.BTOLER) GOTO 210
C     WRITE(M2,9010) T,P
      ERFLAG=1.
      RETURN
  210 IF(P/PSAT.GT.TTOLER) GOTO 240
  220 QUAL=2.0
      D=1.0E-06
      GOTO 260
  240 D=0.66569
      QUAL=-2.0
  260 CALL VFIND(TR,P,D)
      CALL ENTH(TR,D,H,DHDT,DHDD)
      CALL ENTR(TR,D,S,DSDT,DSDD)
      V=1.0/(D*WM)
      CALL PRINTC(TR,P,H,S,V,QUAL,0.0,0.0,0.0,0.0,0.0,0.0,LFTYPE,NPRIN)
      RETURN
  400 T=FGIVEN
      QUAL=SGIVEN
      TR=T+ABST
      IF(QUAL.LE.1.0.AND.QUAL.GE.0.0) GOTO 410
C     WRITE(M2,9020)QUAL
      RETURN
  410   IF(T.LE.TCRIT) GOTO 420
C       WRITE(M2,9030)
      RETURN
  420 TCRITR=TCRIT+ABST
      CALL PRESAT(TR,P,DL,DV,DCRIT,TCRITR,LFTYPE)
      CALL SATC(TR,DL,DV,HL,SL,HV,SV)
      S=SV*QUAL+SL*(1.0-QUAL)
      H=HV*QUAL+HL*(1.0-QUAL)
      VV=1.0/(DV*WM)
      VL=1.0/(DL*WM)
      V=VV*QUAL+VL*(1.0-QUAL)
      CALL PRINTC(TR,P,H,S,V,QUAL,HL,SL,VL,HV,SV,VV,LFTYPE,NPRIN)
      RETURN
  600 P=FGIVEN
      QUAL=SGIVEN
      IF(QUAL.LE.1.0.AND.QUAL.GE.0.0)GOTO 610
C     WRITE(M2,9020) QUAL
      RETURN
  610 IF(P.LE.PCRIT) GOTO 620
```

```
c       WRITE(M2,9040)
        RETURN
  620   CALL TEMSAT(P,TR,DL,DV,TCRIT,DCRIT)
        CALL SATC(TR,DL,DV,HL,SL,HV,SV)
        S=SV*QUAL+SL*(1.0-QUAL)
        H=HV*QUAL+HL*(1.0-QUAL)
        VL=1.0/(DL*WM)
        VV=1.0/(DV*WM)
        V=VV*QUAL+VL*(1.0-QUAL)
        CALL PRINTC(TR,P,H,S,V,QUAL,HL,SL,VL,HV,SV,VV,LFTYPE,NPRIN)
        RETURN
  800   P=FGIVEN
        S=SGIVEN
        IF(P.LT.PCRIT) GOTO 820
        TR=TCRIT*1.1
        DV=1.01*DCRIT
        GOTO 840
  820   CALL TEMSAT(P,TR,DL,DV,TCRIT,DCRIT)
        CALL SATC(TR,DL,DV,HL,SL,HV,SV)
        IF(S.LT.0.0) GOTO 830
        IF(S/SV.GT.TTOLER) GOTO 840
        IF(S/SL.LT.BTOLER) GOTO 860
        GOTO 835
  830   IF(S/SV.LT.BTOLER) GOTO 840
        IF(S/SL.GT.TTOLER) GOTO 860
  835   QUAL=(S-SL)/(SV-SL)
        H=HV*QUAL+HL*(1.0-QUAL)
        VL=1.0/(DL*WM)
        VV=1.0/(DV*WM)
        V=VV*QUAL+VL*(1.0-QUAL)
        CALL PRINTC(TR,P,H,S,V,QUAL,HL,SL,VL,HV,SV,VV,LFTYPE,NPRIN)
        RETURN
  840   QUAL=2.0
        DV=0.01
        CALL PSKNOW(P,S,TR,DV)
        D=DV
        GOTO 880
  860   QUAL=-2.0
        DL=0.55
        CALL PSKNOW(P,S,TR,DL)
        D=DL
  880   CALL ENTH(TR,D,H,DHDT,DHDD)
        V=1.0/(D*WM)
        CALL PRINTC(TR,P,H,S,V,QUAL,0.0,0.0,0.0,0.0,0.0,0.0,LFTYPE,NPRIN)
        RETURN
 1000   P=FGIVEN
        H=SGIVEN
        IF(P.LT.PCRIT) GOTO 1020
        TR=TCRIT*1.1
        DV=1.01*DCRIT
        GOTO 1040
 1020   CALL TEMSAT(P,TR,DL,DV,TCRIT,DCRIT)
        CALL SATC(TR,DL,DV,HL,SL,HV,SV)
        IF(H.LE.0.0)GOTO 1030
        IF(H/HV.GT.TTOLER) GOTO 1040
        IF(H/HL.LT.BTOLER) GOTO 1060
        GOTO 1035
 1030   IF(H/HV.LT.BTOLER)GOTO 1040
        IF(H/HL.GT.TTOLER) GOTO 1060
 1035   QUAL=(H-HL)/(HV-HL)
        S=SV*QUAL+SL*(1.0-QUAL)
        VL=1.0/(DL*WM)
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        VV=1.0/(DV*WM)
          if (qual.lt.0.0.and.qual.gt.-2.0) qual=0.0
        V=VV*QUAL+VL*(1.0-QUAL)
        CALL PRINTC(TR,P,H,S,V,QUAL,HL,SL,VL,HV,SV,VV,LFTYPE,NPRIN)
        RETURN
 1040   QUAL=2.0
        DV=0.01
        CALL PHKNOW(P,H,TR,DV)
        D=DV
        GOTO 1080
 1060   QUAL=-2.0
        DL=0.55
        CALL PHKNOW(P,H,TR,DL)
        D=DL
 1080   CALL ENTR(TR,D,S,DSDT,DSDD)
        V=1.0/(D*WM)
        CALL PRINTC(TR,P,H,S,V,QUALL,0.0,0.0,0.0,0.0,0.0,0.0,
     #    LFTYPE,NPRIN)
        RETURN
 1200   T=FGIVEN
        TR=FGIVEN+ABST
        V=SGIVEN
        D=1.0/(V*WM)
        IF(T.GE.TCRIT) GOTO 1240
        CALL PRESAT(TR,P,DL,DV,DCRIT,TCRITR,LFTYPE)
        IF(D/DL.LT.BTOLER) GOTO 1260
        IF(D/DV.GT.TTOLER) GOTO 1240
        CALL SATC(TR,DL,DV,HL,SL,HV,SV)
        QUAL=(D-DL)/(DV-DL)
        VL=1.0/(DL*WM)
        VV=1.0/(DV*WM)
        H=HV*QUAL+HL*(1.0-QUAL)
        S=SV*QUAL+SL*(1.0-QUAL)
        CALL PRINTC(TR,P,H,S,V,QUAL,HL,SL,VL,HV,SV,VV,LFTYPE,NPRIN)
        RETURN
 1240   QUAL=2.0
        GOTO 1280
 1260   QUAL=-2.0
 1280   CALL PRES(TR,D,P,DPDT,DPDD)
        CALL ENTH(TR,D,H,DHDT,DHDD)
        CALL ENTR(TR,D,S,DSDT,DSDD)
        CALL PRINTC(TR,P,H,S,V,QUAL,0.0,0.0,0.0,0.0,0.0,0.0,LFTYPE,NPRIN)
        RETURN
 9050   FORMAT(1H ,4X,'***ERROR IN CARBON, THE FLUID',A6,'CANNOT BE
     1EVALUATED, CARBON TERMINATED')
 9010   FORMAT(1H ,4X,'***ERROR IN CARBON, THE TEMPERATURE',F10.2,
     1'AND THE PRESSURE',F10.4,'DEFINE A SATURATION STATE, CARBON
     2 TERMINATED')
 9020   FORMAT(1H ,4X,'***ERROR IN CARBON, A QUALITY OF,'F8.2,'IS
     1MEANINGLESS')
 9030   FORMAT(1H ,4X,'***ERROR IN CARBON, A SATURATION STATE DOES NOT
     1EXIST FOR TEMPERATURES GREATER THAN THE CRITICAL TEMPERATURE')
 9040   FORMAT(1H ,4X,'***ERROR IN CARBON, A SATURATION STATE DOES NOT
     1EXIST FOR PRESSURES GREATER THAN THE CRITICAL PRESSURE')
 9000   FORMAT(1H ,4X,'***ERROR IN CARBON, THE CYCLE',A6,'CANNOT BE
     1EVALUATED')
        END
C    _____
        SUBROUTINE SETUP(GIVEN,PCRIT,TCRIT,DCRIT)
C THIS SUBROUTINE SETS UP THE REQUIRED COEFFICIENTS FOR THE PARTICULAR
C FLUID TO BE ANALYZED
        COMMON/CAR1/C(11),CS(6),CH(6),WM,R,CONVR,LIMIT,ABST,TTOLER,BTOLER
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      DIMENSION GIVEN(27)
      DO 100 I=1,11
      C(I)=GIVEN(I)
  100 CONTINUE
      DO 200 I=1,6
      CS(I)=GIVEN(I+11)
      CH(I)=GIVEN(I+17)
  200 CONTINUE
      PCRIT=GIVEN(24)
      TCRIT=GIVEN(25)
      DCRIT=GIVEN(26)
      WM=GIVEN(27)
      RETURN
      END
C     _____
      SUBROUTINE VFIND(T,P,D)
C THIS SUBROUTINE FINDS THE DENSITY GIVEN TEMPERATURE AND PRESSURE FOR
C COMPRESSED LIQUID AND SUPERHEATED VAPOR STATES
      COMMON/CAR1/C(11),CS(6),CH(6),WM,R,CONVR,LIMIT,ABST,TTOLER,BTOLER
      PARAMETER (M2=6)
      DLAST=D
      CALL PRES(T,D,PCAL,DPDT,DPDD)
      DO 100 I=1,LIMIT
      D=DLAST-(PCAL-P)/DPDD
      IF(D.LE.0.0) D=DLAST/10.0
      CALL PRES(T,D,PCAL,DPDT,DPDD)
      IF(PCAL/P.GT.BTOLER.AND.PCAL/P.LT.TTOLER) RETURN
      DLAST=D
  100 CONTINUE
C     WRITE(M2,9000) LIMIT
 9000 FORMAT(1H ,4X,'***VFIND FAILED TO CONVERGE IN',I6,'ITERATIONS')
      RETURN
      END
C
      SUBROUTINE ENTH(T,D,H,DHDT,DHDD)
C THIS SUBROUTINE CALCULATES THE ENTHALPY GIVEN DENSITY AND
C TEMPERATURE
      COMMON/CAR1/C(11),CS(6),CH(6),WM,R,CONVR,LIMIT,ABST,TTOLER,BTOLER
      TERM1=(C(4)*R*T-2.0*C(2)-4.0*C(6)/T**2+5.0*C(8)/T**3-6.0*C(9)
     1 /T**4)
      TERM2=(2.0*C(3)*R*T-3.0*C(1)-4.0*C(7)/T)
      TERM3=C(10)*(6.0*C(1)+7.0*C(7)/T)
      TERM4=C(5)*(3.0-(3.0+0.5*C(11)*D**2-C(11)**2*D**4)*EXP(-C(11)*
     1 D**2))/C(11)
      H=TERM1*D+TERM2*D**2/2.0+TERM3*D**5/5.0+TERM4/T**2
      DHDD=TERM1+TERM2*D+TERM3*D**4+C(5)/(C(11)*T**2)*(5.0*C(11)*D+5.0*
     1 C(11)**2*D**3-2.0*C(11)**3*D**5)*EXP(-C(11)*D**2)
      TERM1=(C(4)*R+8.0*C(6)/T**3-15.0*C(8)/T**4+24.0*C(9)/T**5)*D
      TERM2=0.5*(2.0*C(3)*R+4.0*C(7)/T**2)*D**2
      TERM3=-C(10)*D**5*7.0*C(7)/(T**2*5.0)
      TERM4=-2.0*TERM4/T**3
      H=H*CONVR/WM+CH(1)+CH(2)*T+CH(3)*T**2+CH(4)*T**3+CH(5)*T**4+CH(6)
     1 *T**5
      DHDD=DHDD*CONVR/WM
      DHDT=(TERM1+TERM2+TERM3+TERM4)*CONVR/WM+CH(2)+2.0*CH(3)*T+3.0
     1*CH(4)*T**2+CH(5)*T**3*4.0+5.0*CH(6)*T**4
      RETURN
      END
C     _____
      SUBROUTINE ENTR(T,D,S,DSDT,DSDD)
C THIS SUBROUTINE CALCULATES THE ENTROPY GIVEN DENSITY AND TEMPERATURE
      COMMON/CAR1/C(11),CS(6),CH(6),WM,R,CONVR,LIMIT,ABST,TTOLER,BTOLER
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```
      TERM1=C(4)*R+2.0*C(6)/T**3-3.0*C(8)/T**4+4.0*C(9)/T**5
      TERM2=C(3)*R+C(7)/T**2
      TERM3=1.0-(1.0+0.5*C(11)*D**2)*EXP(-C(11)*D**2)
      S=CONVR*(-R*LOG(D*R*T)-TERM1*D-0.5*TERM2*D**2
     #+C(10)*C(7)*D**5/(5.0*T**2)+2.0*C(5)*TERM3/(C(11)*T**3))/WM+CS(1)
     #+CS(2)*T+CS(3)*T**2+CS(4)*T**3+CS(5)*T**4+CS(6)*T**5
      DSDT=CONVR*(-R/T-(-6.0*C(6)/T**4+12.0*C(8)/T**5-20.0*C(9)/T**6)*D
     #+C(7)*D**2/T**3-0.4*C(10)*C(7)*D**5/T**3-6.0*C(5)*TERM3/
     #(C(11)*T**4))/WM+CS(2)+2.0*CS(3)*T+3.0*CS(4)*T**2+4.0*CS(5)*T**3
     #+5.0*CS(6)*T**4
      TERM1=-(C(4)*R+2.0*C(6)/T**3-3.0*C(8)/T**4+4.0*C(9)/T**5)
      TERM2=-(C(3)*R+C(7)/T**2)*D
      DSDD=(-R/D+TERM1+TERM2+C(10)*C(7)*D**4/T**2+2.0*C(5)*
     #(D+C(11)*D**3)*EXP(-C(11)*D**2)/T**3)*CONVR/WM
      RETURN
      END
C     _____
      SUBROUTINE PRINTC(T,P,H,S,V,QUAL,HL,SL,VL,HV,SV,VV,LFTYPE,NPRIN)
      CHARACTER*6 LFTYPE
      PARAMETER (M2=6)
      COMMON/CAR1/C(11),CS(6),CH(6),WM,R,CONVR,LIMIT,ABST,TTOLER,BTOLER
      T=T-ABST
      IF(NPRIN.EQ.0) RETURN
C     WRITE(M2,9000) LFTYPE
C     WRITE(M2,9010) T,P
      IF(QUAL.LE.1.0.AND.QUAL.GE.0.0) GOTO 3280
C     IF(QUAL.GT.1.0) WRITE(M2,9020)
C     IF(QUAL.LT.0.0) WRITE(M2,9030)
      GOTO 3370
3280  continue
C     WRITE(M2,9040) QUAL
C     WRITE(M2,9050)
C     WRITE(M2,9070) HV,HL
C     WRITE(M2,9080) SV,SL
C     WRITE(M2,9060) VV,VL
3370  continue
C     WRITE(M2,9090)
C     WRITE(M2,9070) H
C     WRITE(M2,9080) S
C     WRITE(M2,9060) V
9000  FORMAT(1H1,4X,'***THERMODYNAMIC PROPERTIES OF ',A6,' USING
     #STARLING-BWR QUATION OF STATE***')
9010  FORMAT(1H ,4X,'TEMPERATURE = ',F7.1,'DEG.F',//,5X,'PRESSURE    =
     #
     #   F10.5,'PSIA')
9020  FORMAT(1H ,4X,'SUPERHEATED VAPOR',//////)
9030  FORMAT(1H ,4X,'COMPRESSED LIQUID',//////)
9040  FORMAT(1H ,4X,'SATURATED LIQUID-VAPOR EQUILIBRIUM',//,5X,'QUALITY
     =
     #  ',F6.4)
9050  FORMAT(1H ,//,35X,'SATURATED',8X,'SATURATED',//,35X,'VAPOR',12X,
     #      'LIQUID',//,5X,60('#'))
9060  FORMAT(1H ,4X,'SPECIFIC VOLUME (CU.FT/LBM)',5X,F9.4,8X,F9.4,/////
     #      /)
9070  FORMAT(1H ,4X,'ENTHALPY',8X,'(BTU/LBM)',5X,F9.3,8X,F9.3)
9080  FORMAT(1H ,4X,'ENTROPY',9X,'(BTU/LBM-R)',5X,F9.6,8X,F9.6)
9090  FORMAT(1H ,//////)
      RETURN
      END
C     _____
      SUBROUTINE PRESAT(T,P,DL,DV,DCRIT,TCRITR,FTYPE)
C     THIS SUBROUTINE FINDS SATURATION PRESSURE AND SATURATED LIQUID AND
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C   VAPOR DENSITIES GIVEN TEMPERATURE
      CHARACTER*6 FTYPE
      COMMON/CAR1/C(11),CS(6),CH(6),WM,R,CONVR,LIMIT,ABST,TTOLER,BTOLER
      PARAMETER (M2=6)
      TRED=T/TCRITR
      DL=DCRIT*(2.0+2.5*(1.0-TRED))
      IF(FTYPE.NE.'PROP  ') GOTO 10
      DL=DCRIT*(1.8+3.4*(1.0-TRED)-2.7*(1.0-TRED)**2.0)
      DV=DCRIT/(275.0*(1.0-TRED))
      GOTO 200
   10 IF(FTYPE.NE.'ISOP  ') GOTO 20
      DL=DCRIT*(1.8+3.4*(1.0-TRED)-2.7*(1.0-TRED)**2.0)
      DV=DCRIT/(225.0*(1.0-TRED))
      GOTO 200
   20 IF(FTYPE.NE.'PENT  ') GOTO 30
      DL=DCRIT*(1.8+3.4*(1.0-TRED)-2.7*(1.0-TRED)**2.0)
      DV=DCRIT/(300.0*(1.0-TRED)-6.0)
      GOTO 200
   30 DV=DCRIT/(150.0*(1.0-TRED))
  200 CALL FUGAC(T,DL,FL,DFLDT,DFLDDL)
      CALL FUGAC(T,DV,FV,DFVDT,DFVDDV)
      CALL PRES(T,DL,PL,DPLDT,DPLDDL)
      CALL PRES(T,DV,PV,DPVDT,DPVDDV)
      DVLAST=DV
      DLLAST=DL
      DO 1000 I=1,LIMIT
      FP=PL-PV
      FF=FL-FV
      DFPDDV=-DPVDDV
      DFPDDL=DPLDDL
      DFFDDV=-DFVDDV
      DFFDDL=DFLDDL
      XJACOB=DFPDDV*DFFDDL-DFPDDL*DFFDDV
      DV=DVLAST-(FP*DFFDDL-FF*DFPDDL)/XJACOB
      DL=DLLAST-(FF*DFPDDV-FP*DFFDDV)/XJACOB
      IF(DV.LE.0.0) DV=DVLAST/10.0
      IF(DL.LE.0.0) DL=DLLAST/10.0
      IF(DV.GE.DCRIT) DV=DCRIT*0.9
      IF(DL.LE.DCRIT) DL=DCRIT*1.1
      IF(DL.GT.1.0) DL=DLLAST*1.01
      CALL FUGAC(T,DL,FL,DFLDT,DFLDDL)
      CALL FUGAC(T,DV,FV,DFVDT,DFVDDV)
      CALL PRES(T,DL,PL,DPLDT,DPLDDL)
      CALL PRES(T,DV,PV,DPVDT,DPVDDV)
      P=(PV+PL)/2.0
      IF(FL/FV.LT.TTOLER.AND.FL/FV.GT.BTOLER.AND.PL/PV.LT.TTOLER.
     #AND.PL/PV.GT.BTOLER) RETURN
      DLLAST=DL
      DVLAST=DV
 1000 CONTINUE
C     WRITE(M2,9000) LIMIT
C9000 FORMAT(                       )
      RETURN
      END
C     _____
      SUBROUTINE SATC(T,DL,DV,HL,SL,HV,SV)
C   THIS SUBROUTINE DETERMINES SATURATED LIQUID AND VAPOR PROPERTIES
      CALL ENTH(T,DL,HL,DHLDT,DHLDD)
      CALL ENTR(T,DL,SL,DSLDT,DSLDD)
      CALL ENTH(T,DV,HV,DHVDT,DHVDD)
      CALL ENTR(T,DV,SV,DSVDT,DSVDD)
      RETURN
```

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        END
C  _____
        SUBROUTINE TEMSAT(P,T,DL,DV,TCRIT,DCRIT)
C  THIS SUBROUTINE FINDS THE SATURATION TEMPERATURE AND
C  SATURATED LIQUID AND
C  VAPOR DENSITIES GIVEN PRESSURE
        COMMON/CAR1/C(11),CS(6),CH(6),WM,R,CONVR,LIMIT,ABST,TTOLER,BTOLER
        DIMENSION XJACOB(3,3),F(3),DX(3)
        PARAMETER (M2=6)
        TCRITR=TCRIT+ABST
        T=640.0
        DV=DCRIT/20.0
        DL=DCRIT*2.5
        TLAST=T
        DVLAST=DV
        DLLAST=DL
        CALL PRES(T,DL,PL,DPLDT,DPLDDL)
        CALL PRES(T,DV,PV,DPVDT,DPVDDV)
        CALL FUGAC(T,DL,FL,DFLDT,DFLDDL)
        CALL FUGAC(T,DV,FV,DFVDT,DFVDDV)
        DO 1000 I=1,LIMIT
        F(1)=PL-P
        F(2)=PV-P
        F(3)=FV-FL
        XJACOB(1,1)=DPLDDL
        XJACOB(1,2)=0.0
        XJACOB(1,3)=DPLDT
        XJACOB(2,1)=0.0
        XJACOB(2,2)=DPVDDV
        XJACOB(2,3)=DPVDT
        XJACOB(3,1)=-DFLDDL
        XJACOB(3,2)=DFVDDV
        XJACOB(3,3)=DFVDT-DFLDT
        CALL INVERT(XJACOB,F,DX)
        DL=DLLAST-DX(1)
        DV=DVLAST-DX(2)
        T=TLAST-DX(3)
  750   IF(T.LE.0.0)T=TLAST/10.0
        IF(DL.LE.0.0) DL=DLLAST/10.0
        IF(DV.LE.0.0) DV=DVLAST/10.0
        IF(DV.GE.0.55) DV=DVLAST*2.0
        IF(DL.GE.1.0) DL=DLLAST*2.0
        IF(T.GT.TCRITR) T=TCRITR
        CALL PRES(T,DL,PL,DPLDT,DPLDDL)
        CALL PRES(T,DV,PV,DPVDT,DPVDDV)
        CALL FUGAC(T,DL,FL,DFLDT,DFLDDL)
        CALL FUGAC(T,DV,FV,DFVDT,DFVDDV)
        IF(PL/P.LT.TTOLER.AND.PL/P.GT.BTOLER.AND.PV/P.LT.TTOLER.
       #AND.PV/P.GT.BTOLER.AND.FL/FV.LT.TTOLER.AND.FL/FV.GT.
       #BTOLER) RETURN
        DLLAST=DL
        DVLAST=DV
        TLAST=T
 1000   CONTINUE
C       WRITE(           )
C9000   FORMAT(          )
        RETURN
        END
C  _____
        SUBROUTINE PSKNOW(P,S,T,D)
C  THIS SUBROUTINE FINDS DENSITY AND TEMPERATURE GIEN PRESSURE AND
C  ENTROPY
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C  FOR COMPRESSED LIQUID AND SUPERHEATED VAPOR STATES
      COMMON/CAR1/C(11),CS(6),CH(6),WM,R,CONVR,LIMIT,ABST,TTOLER,BTOLER
      PARAMETER (M2=6)
      DLAST=D
      TLAST=T
      CALL PRES(T,D,PCAL,DPDT,DPDD)
      CALL ENTR(T,D,SCAL,DSDT,DSDD)
      DO 1000 I=1,LIMIT
      XJACOB=DPDD*DSDT-DPDT*DSDD
      D=DLAST-((PCAL-P)*DSDT-(SCAL-S)*DPDT)/XJACOB
      T=TLAST-((SCAL-S)*DPDD-(PCAL-P)*DSDD)/XJACOB
      IF(T.LE.0.0) T=TLAST/10.0
      IF(D.LE.0.0) D=DLAST/10.0
      CALL PRES(T,D,PCAL,DPDT,DPDD)
      CALL ENTR(T,D,SCAL,DSDT,DSDD)
      IF(PCAL/P.LT.TTOLER.AND.PCAL/P.GT.BTOLER.AND.SCAL/S.LT.TTOLER.
     #AND.SCAL/S.GT.BTOLER)RETURN
      DLAST=D
      TLAST=T
 1000 CONTINUE
C     WRITE(M2,9000) LIMIT
 9000 FORMAT(1H ,4X,'***PSKNOW FAILED TO CONVERGE IN',I6,' ITERATIONS')
      RETURN
      END
C     _____
      SUBROUTINE PHKNOW(P,H,T,D)
C  THIS SUBROUTINE FINDS THE DENSITY AND TEMPERATURE GIVEN PRESSURE AND
C  ENTHALPY FOR COMPRESSED LIQUID AND SUPERHEATED VAPOR STATES
      COMMON/CAR1/C(11),CS(6),CH(6),WM,R,CONVR,LIMIT,ABST,TTOLER,BTOLER
      PARAMETER (M2=6)
      TT=1.0005
      BT=.9995
      DLAST=D
      TLAST=T
      CALL PRES(T,D,PCAL,DPDT,DPDD)
      CALL ENTH(T,D,HCAL,DHDT,DHDD)
      DO 1000 I=1,LIMIT
      XJACOB=DPDD*DHDT-DPDT*DHDD
      D=DLAST-((PCAL-P)*DHDT-(HCAL-H)*DPDT)/XJACOB
      T=TLAST-((HCAL-H)*DPDD-(PCAL-P)*DHDD)/XJACOB
      IF(D.LE.0.0) D=DLAST/10.0
      IF(T.LE.0.0) T=TLAST/10.0
      CALL PRES(T,D,PCAL,DPDT,DPDD)
      CALL ENTH(T,D,HCAL,DHDT,DHDD)
      IF(PCAL/P.LT.TT.AND.PCAL/P.GT.BT.AND.HCAL/H.LT.TT.
     #AND.HCAL/H.GT.BT) RETURN
      DLAST=D
      TLAST=T
 1000 CONTINUE
C     WRITE(M2,9000)LIMIT
 9000 FORMAT(1H ,4X,'***PHKNOW FAILED TO CONVERGE IN',I6,' ITERATIONS')
      RETURN
      END
C     _____
      SUBROUTINE FUGAC(T,D,F,DFDT,DFDD)
      COMMON/CAR1/C(11),CS(6),CH(6),WM,R,CONVR,LIMIT,ABST,TTOLER,BTOLER
      TERM1=C(4)*R*T-C(2)-C(6)/T**2+C(8)/T**3-C(9)/T**4
      TERM2=C(3)*R*T-C(1)-C(7)/T
      TERM3=C(1)+C(7)/T
      TERM4=1.0-(1.0-0.5*C(11)*D**2-C(11)**2*D**4)*EXP(-C(11)*D**2)
      F=LOG(D*R*T)+2.0*TERM1*D/(R*T)+3.0*D**2*TERM2/(2.0*R*T)+6.0*C(10)
     #*TERM3*D**5/(5.0*R*T)+C(5)*TERM4/(C(11)*R*T**3)
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      F=EXP(F)
      DFDD=F*(1.0/D+2.0*TERM1/(R*T)+3.0*TERM2*D/(R*T)+6.0*C(10)*D**4
     #*TERM3/(R*T)+C(5)/(R*C(11)*T**3)*(3.0*C(11)*D+3.0*C(11)**2*D**3
     #-2.0*D**5*C(11)**3)*EXP(-C(11)*D**2))
      TERM1=C(2)+3.0*C(6)/T**2-4.0*C(8)/T**3+5.0*C(9)/T**4
      TERM2=C(1)+2.0*C(7)/T
      DFDT=F*(1.0/T+2.0*TERM1*D/(T**2*R)+3.0*TERM2*D**2/(2.0*R*T**2)
     #-6.0*C(10)*TERM2*D**5/(5.0*R*T**2)-3.0*C(5)*TERM4/(C(11)*R*T**4))
      RETURN
      END
C     _____
      SUBROUTINE PRES(T,D,P,DPDT,DPDD)
      COMMON/CAR1/C(11),CS(6),CH(6),WM,R,CONVR,LIMIT,ABST,TTOLER,BTOLER
      TERM1=C(4)*R*T-C(2)-C(6)/T**2+C(8)/T**3-C(9)/T**4
      TERM2=C(3)*R*T-C(1)-C(7)/T
      TERM3=C(1)+C(7)/T
      TERM4=1.0+C(11)*D**2
      P=D*R*T+TERM1*D**2+TERM2*D**3+C(10)*TERM3*D**6+C(5)*D**3*TERM4*
     #EXP(-C(11)*D**2)/T**2
      DPDD=R*T+2.0*TERM1*D+3.0*TERM2*D**2+6.0*C(10)*TERM3*D**5
     #+3.00*C(5)*D**2*TERM4*EXP(-C(11)*D**2)/T**2-2.0*C(11)**2*D**6
     #*C(5)*EXP(-C(11)*D**2)/T**2
      DPDT=D*R+D**2*(C(4)*R+2.0*C(6)/T**3-3.0*C(8)/T**4+4.0+C(9)/
     #T**5)+D**3*(C(3)*R+C(7)/T**2)-D**6*C(10)*C(7)/T**2-2.0*C(5)*D**3
     #*TERM4*EXP(-C(11)*D**2)/T**3
      RETURN
      END
C     _____
      SUBROUTINE INVERT(XJACOB,F,DX)
C     THIS SUBROUTINE SOLVES THREE SIMULTANEOUS EQUATIONS
C     BY GUASSIAN ELIMINATION
      DIMENSION XJACOB(3,3),DX(3),F(3),W(3,4)
      DO 5 I=1,3
      DO 5 J=1,4
      IF(J-4)2,3,5
    2 W(I,J)=XJACOB(I,J)
      GOTO 5
    3 W(I,J)=F(I)
    5 CONTINUE
      N=0
      DO 100 K=1,2
      N=N+1
      DO 95 L=2,3
      IF(K-L)10,90,90
   10 C=-W(L,N)/W(K,N)
      DO 80 M=1,4
      W(L,M)=W(L,M)+C*W(K,M)
   80 CONTINUE
   90 CONTINUE
   95 CONTINUE
  100 CONTINUE
      DX(3)=W(3,4)/W(3,3)
      DX(2)=(W(2,4)-DX(3)*W(2,3))/W(2,2)
      DX(1)=(W(1,4)-DX(3)*W(1,3)-DX(2)*W(1,2))/W(1,1)
      RETURN
      END
C     _____
      SUBROUTINE FREON(CYCLE,FGIVEN,SGIVEN,FTYPE,H,S,V,T,PSIA,
     #   HV,SV,VV,HL,SL,VL,QUAL,NPRT)
C
C     THIS SUBROUTINE CALCULATES THE THERMODYNAMIC PROPERTIES OF FREONS
C     BY USING THE MARTIN-NOU EQUATION OF STATE.
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C
      CHARACTER FTYPE*6,CYCLE*2
      PARAMETER (M2=6)
      DIMENSION F113(4,12),F114(4,12),F11(4,12),F12(4,12),F13(4,12),
     #F14(4,12),F21(4,12),F22(4,12),F23(4,12)
      COMMON/FREON1/Q(4,12),TTOLER,BTOLER,LIMIT,DERROR,NTYPE
      DATA LIMIT,DERROR,TTOLER,BTOLER/50,1.0E-10,1.001,0.999/
      DATA((F113(I,J),I=1,4),J=1,12)/33.0655,-4330.98,-9.2635,
     #0.0020539,0.0,0.0,0.0,0.0,0.0,0.05728,0.0,417.4,122.872,
     #-4.035,0.002618,0.0,-0.0128,-0.0214,5.0E-05,0.0,-6.36E-05,0.0,
     #0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.07963,1.159E-04,0.0,
     #0.0,0.0,0.0,25.198,-0.40552,0.1699,459.6,109.49,3.0,0.02781,0.0,
     #0.0,0.0,498.9/
      DATA ((F114(I,J),I=1,4),J=1,12)/27.071306,-5113.7021,-6.3086761,
     #6.913003E-04,0.78142111002,768.35,0.0,0.0,0.0,0.062780807,
     #5.914907E-03,294.35,36.32,-2.3856704,1.0801207E-03,-6.5643648,
     #0.021776,0.034055687,-5.3336494E-06,0.16366057,0.63649,
     #-3.857481E-04,0.0,0.0,6.7186,1.6017659E-06,6.2632341E-10,
     #-1.0165314E-05,1.97E-06,0.0,0.0,0.0,0.0175,3.49E-04,-1.67E-07,
     #0.0,0.0,25.33966211,-0.1151271756,0.15842,459.6,95.4,2.0,
     #0.027533,0.0,3.0,0.0,473.187/
      DATA((F11(I,J),I=1,4),J=1,12)/42.14702865,-4344.343807,
     #-12.84596753,0.004008372507,0.0313605356,862.07,0.0,0.0,0.0,
     #0.078117,0.00190,388.47,34.57,-3.126759,1.318523E-03,-35.769990,
     #57.63811,-0.025341,4.8751212E-05,1.220367,43.63220,1.687277E-03,
     #-1.805062E-06,0.0,-42.82356,-2.358930E-05,2.448303E-08,
     #-1.478379E-04,36.70663,1.057504E08,-9.472103E04,0.0,0.023815,
     #2.798823E-04,-2.123734E-07,5.999018E-11,-336.807030,50.5418,
     #-0.0918395,0.17219,459.6,112.080,1.0,0.028927,0.0,4.50,580.00,
     #639.50/
      DATA((F12(I,J),I=1,4),J=1,12)/39.88381727,-3436.632228,
     #-12.47152228,0.004730442442,0.0,0.0,0.0,0.0,0.0,0.088734,
     #0.00065093886,233.70,34.84,-3.409727134,0.00159434848,
     #-56.7627671,0.02696,0.06023944654,-1.879618431E-05,1.311399084,
     #0.834921,-0.000548737007,0.0,0.0,6.02683,0.0,3.468834E-09,
     #-2.54390678E-05,-0.655549E-05,0.0,0.0,0.0,0.0080945,0.000332662,
     #-2.413896E-07,6.72363E-11,0.0,-39.55655122,-0.0165379361,0.1359,
     #459.6,78.86,2.0,0.02870,0.0,5.475,0.0,596.9/
      DATA((F13(I,J),I=1,4),J=1,12)/25.96797498,-2709.538217,
     #-7.172343913,0.00254515398,0.2803010913,546.00,0.0,0.0,0.0,
     #0.102728,0.0048,84.00,36.06996128,-3.083417,2.341695E-03,
     #-18.212643,0.01566,0.058854,-5.671268E-05,0.571958,1.110,
     #-1.026061E-03,1.338679E-06,0.0,6.665,5.290649E-06,-7.395111E-9,
     #-3.874233E-05,3.245E-05,7.378601E07,-7.435565E04,0.0,0.01602,
     #2.823E-04,-1.159E-07,0.0,0.0,20.911,-0.05676,0.08898,459.6,
     #45.271,2.0,0.0277239,0.0,4.00,625.00,561.30/
      DATA((F14(I,J),I=1,4),J=1,12)/20.7154389,-2467.505285,
     #-4.69017025,0.00064798076,0.770707795,424.0,0.0,0.0,0.0,
     #0.1219336,0.0015,-50.1,39.06,-2.162959,2.135114E-03,-18.941131,
     #69.56848907,4.404057E-03,1.282818E-05,0.539776,4.58661139,
     #1.921072E-04,-3.918263E-07,0.0,36.17166615,-4.481049E-06,
     #9.062318E-09,-4.836678E-05,-8.05898583,5.838823E07,-9.263923E04,
     #0.0,3.00559282E-02,2.37043352E-04,-2.85660077E-08,
     #-2.95338806E-11,0.0,86.102162,0.36172528,0.5284,459.6,100.636,
     #1.0,0.02560163,0.0,4.00,661.199997,543.16/
      DATA((F21(I,J),I=1,4),J=1,12)/42.7908,-4261.34,-13.0295,
     #0.0039851,0.0,0.0,0.0,0.0,0.0,0.10427,0.0,0.0,
     #812.9,116.37962,-7.316,0.00464210,
     #0.0,-0.03106808,-0.20382376,0.0003593,0.0,-0.0000501,0.0,0.0,0.0,
     #0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0427,0.000140,0.0,0.0,0.0,0.0,
     #0.0,0.1906,459.6,120.45,3.0,0.030675,0.0,0.0,0.0,750.0/
      DATA((F22(I,J),I=1,4),J=1,12)/29.35754453,
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#-3845.193152,-7.86103122,0.002190939044,
#0.445746703,686.1,0.0,0.0,0.0,0.124098,
#0.002,204.81,32.76,-4.353547,0.002407252,-44.066868,
#54.6344093,-0.017464,7.62789E-05,
#1.483763,36.74892,0.002310142,-3.605723E-06,
#0.0,-22.2925657,-3.724044E-05,5.355465E-08,-1.845051E-04,
#20.47328862,1.363387E08,-1.672612E05,0.0,0.02812836,2.255408E-04,
#-6.509607E-08,0.0,257.341,62.4009,-0.0453335,0.16016,459.69,
#91.329,1.0,0.030525,0.0,4.2,548.2,721.906/
   DATA((F23(I,J),I=1,4),J=1,12)/328.90853,-7952.76913,
#-144.5142304,0.2421150182,0.0,0.0,0.0,
#-2.128066524E-04,9.43495542E-08,0.153270,0.00125,
#78.73,32.7758,-4.679499,3.472778E-03,-159.775232,63.37784,
#-0.012475,7.733388E-05,5.941212,-25.30533,2.068042E-03,
#-3.684238E-06,0.0,144.16182,-3.868546E-05,6.455643E-08,
#-7.394214E-04,-106.13280,7.502357E07,-1.114202E05,0.0,0.07628087,
#-7.561805E-06,3.9065696E-07,-2.454905E-10,0.0,0.0,0.0,0.1198,
#459.6,60.77,1.0,0.030510,0.0,5.50,520.00,701.42/
   RJ=0.185053
   H=0.0
   S=0.0
   V=0.0
   T=0.0
   PSIA=0.0
   HV=0.0
   SV=0.0
   VV=0.0
   HL=0.0
   SL=0.0
   VL=0.0
   QUAL=0.0
   IF(FTYPE.EQ.'F113   ') GOTO 10
   IF(FTYPE.EQ.'F114   ') GOTO 20
   IF(FTYPE.EQ.'F11    ') GOTO 30
   IF(FTYPE.EQ.'F12    ') GOTO 40
   IF(FTYPE.EQ.'F13    ') GOTO 50
   IF(FTYPE.EQ.'F14    ') GOTO 60
   IF(FTYPE.EQ.'F21    ') GOTO 70
   IF(FTYPE.EQ.'F22    ') GOTO 80
   IF(FTYPE.EQ.'F23    ') GOTO 90
C  WRITE(M2,9060) FTYPE
   RETURN
10 DO 15 I=1,4
   DO 15 J=1,12
   Q(I,J)=F113(I,J)
15 CONTINUE
   GOTO 350
20 DO 25 I=1,4
   DO 25 J=1,12
   Q(I,J)=F114(I,J)
25 CONTINUE
   GOTO 350
30 DO 35 I=1,4
   DO 35 J=1,12
   Q(I,J)=F11(I,J)
35 CONTINUE
   GOTO 350
40 DO 45 I=1,4
   DO 45 J=1,12
   Q(I,J)=F12(I,J)
45 CONTINUE
   GOTO 350
```

```
   50 DO 55 I=1,4
      DO 55 J=1,12
      Q(I,J)=F13(I,J)
   55 CONTINUE
      GOTO 350
   60 DO 65 I=1,4
      DO 65 J=1,12
      Q(I,J)=F14(I,J)
   65 CONTINUE
      GOTO 350
   70 DO 75 I=1,4
      DO 75 J=1,12
      Q(I,J)=F21(I,J)
   75 CONTINUE
      GOTO 350
   80 DO 85 I=1,4
      DO 85 J=1,12
      Q(I,J)=F22(I,J)
   85 CONTINUE
      GOTO 350
   90 DO 95 I=1,4
      DO 95 J=1,12
      Q(I,J)=F23(I,J)
   95 CONTINUE
  350 NTYPE=Q(3,11)
      HCRIT=Q(2,11)
      SCRIT=Q(4,10)
      PCRIT=Q(4,12)
      TCRIT=Q(4,3)
      IF(CYCLE.EQ.'TP') GOTO 400
      IF(CYCLE.EQ.'TX') GOTO 600
      IF(CYCLE.EQ.'PX') GOTO 700
      IF(CYCLE.EQ.'PS') GOTO 900
      IF(CYCLE.EQ.'PH') GOTO 1000
      IF(CYCLE.EQ.'TV') GOTO 1100
C     WRITE(M2,9000)
      RETURN
  400 TF=FGIVEN
      PSIA=SGIVEN
      T=TF+Q(1,11)
      IF(TF.LT.Q(4,3)) GOTO 430
      V=1.0/Q(1,4)
      GOTO 480
  430 CALL VPEQM(PSAT,T,1)
      IF(PSIA/PSAT.GT.TTOLER.OR.PSIA/PSAT.LT.BTOLER) GOTO 470
C     WRITE(M2,9010)
      RETURN
  470 IF(PSIA/PSAT.GT.TTOLER) GOTO 500
  480 QUAL=2.0
      CALL VOLUME(T,PSIA,V)
      CALL ENTHAL(PSIA,T,V,H,DHDT,DHDV)
      CALL ENTROP(T,V,S,DSDT,DSDV)
      CALL PRINTF(T,PSIA,QUAL,V,H,S,0.0,0.0,0.0,0.0,0.0,0.0,FTYPE,NPRT)
      RETURN
  500 CALL VOLUME(T,PSAT,V)
      CALL DRVPT(DPSDT,PSAT,T,DPSDT2)
      CALL ENTHAL(PSAT,T,V,H,DHDT,DHDV)
      CALL ENTROP(T,V,S,DSDT,DSDV)
      CALL FLQDEN(VL,T,DVLDT)
      DELTH=RJ*DPSDT*(V-VL)*T
      H=H-DELTH
      S=S-DELTH/T
```

```
          QUAL=-2.0
          CALL PRINTF(T,PSIA,QUAL,VL,H,S,0.0,0.0,0.0,0.0,0.0,0.0,
         #FTYPE,NPRT)
          V=VL
          RETURN
     600  TF=FGIVEN
          QUAL=SGIVEN
          IF(QUAL.LE.1.0.AND.QUAL.GE.0.0) GOTO 610
   c      WRITE(M2,9070) QUAL
          RETURN
     610  T=TF+Q(1,11)
          IF(TF.LE.Q(4,3)) GOTO 630
   c      WRITE(M2,9020) TCRIT
          RETURN
     630  CALL VPEQM (PSIA,T,1)
          GOTO 800
     700  PSIA=FGIVEN
          QUAL=SGIVEN
          IF(QUAL.LE.1.0.AND.QUAL.GE.0.0) GOTO 710
   c      WRITE(M2,9070) QUAL
          RETURN
     710  IF(PSIA.LE.Q(4,12)) GOTO 730
   c      WRITE(M2,9030) PCRIT
          RETURN
     730  CALL VPEQM(PSIA,T,2)
          TF=T-Q(1,11)
     800  IF(TF-Q(4,3)) 830,810,810
     810  V=1.0/Q(4,11)
          GOTO 840
     830  CALL VOLUME(T,PSIA,VV)
     840  CALL SATN(PSIA,T,VV,HV,SV,HL,SL,VL)
          H=(1.0-QUAL)*HL+QUAL*HV
          S=(1.0-QUAL)*SL+QUAL*SV
          V=(1.0-QUAL)*VL+QUAL*VV
          CALL PRINTF(T,PSIA,QUAL,V,H,S,VV,HV,SV,VL,HL,SL,FTYPE,NPRT)
          RETURN
     900  PSIA=FGIVEN
          S=SGIVEN
          IF(PSIA.LT.Q(4,12)) GOTO 910
          IF(S.LE.SCRIT) GOTO 905
          T=Q(4,3)+Q(1,11)
          V=1.0/Q(4,11)
          GOTO 940
     905      continue
   c          WRITE(M2,9040)
          RETURN
     910  CALL VPEQM(PSIA,T,2)
          CALL VOLUME(T,PSIA,V)
          VV=V
          CALL SATN(PSIA,T,VV,HV,SV,HL,SL,VL)
          IF(S/SV.GT.TTOLER) GOTO 940
          IF(S/SL.LT.BTOLER) GOTO 960
          QUAL=(S-SL)/(SV-SL)
          H=(1.0-QUAL)*HL+QUAL*HV
          V=(1.0-QUAL)*VL+QUAL*VV
          CALL PRINTF(T,PSIA,QUAL,V,H,S,VV,HV,SV,VL,HL,SL,FTYPE,NPRT)
          RETURN
     940  CALL SFIND(T,PSIA,V,S)
          CALL ENTHAL(PSIA,T,V,H,DHDT,DHDV)
          QUAL=2.0
          CALL PRINTF(T,PSIA,QUAL,V,H,S,0.0,0.0,0.0,0.0,0.0,0.0,FTYPE,NPRT)
          RETURN
```

```
  960 P=PSIA
       CALL COMPS(P,T,V,S,VL)
       CALL ENTHAL(P,T,V,H,DHDT,DHDV)
       CALL DRVPT(DPSDT,P,T,DPSDT2)
       DELTH=RJ*DPSDT*(V-VL)*T
       H=H-DELTH
       QUAL=-2.0
       CALL PRINTF(T,PSIA,QUAL,VL,H,S,0.0,0.0,0.0,0.0,0.0,0.0,
      #FTYPE,NPRT)
       V=VL
       RETURN
 1000 PSIA=FGIVEN
       H=SGIVEN
       IF(PSIA.LT.Q(4,12))GOTO 1020
       IF(H.GT.HCRIT) GOTO 1010
  c    WRITE(M2,9050)
       RETURN
 1010 T=Q(1,11)+Q(4,3)+10.0
       V=1.0/Q(4,11)
       GOTO 1040
 1020 CALL VPEQM(PSIA,T,2)
       CALL VOLUME(T,PSIA,V)
       VV=V
       CALL SATN(PSIA,T,VV,HV,SV,HL,SL,VL)
       IF(H/HV.GT.TTOLER)GOTO 1040
       IF(H/HL.LT.BTOLER) GOTO 1060
       QUAL=(H-HL)/(HV-HL)
       S=(1.0-QUAL)*SL+QUAL*SV
       V=(1.0-QUAL)*VL+QUAL*VV
       CALL PRINTF(T,PSIA,QUAL,V,H,S,VV,HV,SV,VL,HL,SL,FTYPE,NPRT)
       RETURN
 1040 CALL HFIND(T,PSIA,V,H)
       CALL ENTROP(T,V,S,DSDT,DSDV)
       QUAL=2.0
       CALL PRINTF(T,PSIA,QUAL,V,H,S,0.0,0.0,0.0,0.0,0.0,0.0,FTYPE,NPRT)
       RETURN
 1060 P=PSIA
       CALL COMPH(P,T,V,H,VL)
       CALL ENTROP(T,V,S,DSDT,DSDV)
       CALL DRVPT(DPSDT,P,T,DPSDT2)
       DELTH=RJ*DPSDT*(V-VL)
       S=S-DELTH
       QUAL=-2.0
       CALL PRINTF(T,PSIA,QUAL,VL,H,S,0.0,0.0,0.0,0.0,0.0,
      #   0.0,FTYPE,NPRT)
       V=VL
       RETURN
 1100 TF=FGIVEN
       T=TF+Q(1,11)
       V=SGIVEN
       IF(T.GE.TCRIT)GOTO 1140
       CALL VPEQM(PSAT,T,1)
       CALL FLQDEN(VL,T,DVLDT)
       CALL VOLUME(T,PSAT,VV)
       IF(V/VL.LT.BTOLER) GOTO 1160
       IF(V/VV.GT.TTOLER)GOTO 1140
       CALL SATN(PSAT,T,VV,HV,SV,HL,SL,VL)
       QUAL=(V-VL)/(VV-VL)
       H=(1.0-QUAL)*HL+QUAL*HV
       S=(1.0-QUAL)*SL+QUAL*SV
       CALL PRINTF(T,PSAT,QUAL,V,H,S,VV,HV,SV,VL,HL,SL,FTYPE,NPRT)
       PSIA=PSAT
```

```
      RETURN
1140  CALL EOS(PCAL,T,V,DPDT,DPDV,DPDVDT,D2PDT2)
      CALL ENTHAL(PCAL,T,V,H,DHDT,DHDV)
      CALL ENTROP(T,V,S,DSDT,DSDV)
      QUAL=2.0
      CALL PRINTF(T,PCAL,QUAL,V,H,S,0.0,0.0,0.0,0.0,0.0,0.0,FTYPE,NPRT)
      PSIA=PCAL
      RETURN
1160  CALL VPEQM(PSIA,T,1)
      CALL VOLUME(T,PSIA,VV)
      CALL DRVPT(DPSDT,PSIA,T,DPSDT2)
      CALL ENTROP(T,VV,S,DSDT,DSDV)
      CALL ENTHAL(PSIA,T,VV,H,DHDT,DHDV)
      QUAL=-2.0
      DELTH=RJ*DPSDT*(VV-V)
      S=S-DELTH
      H=H-DELTH*T
      CALL PRINTF(T,PSIA,QUAL,V,H,S,0.0,0.0,0.0,0.0,0.0,0.0,FTYPE,NPRT)
      RETURN
9000  FORMAT(1H ,4X,'***ERROR*** CYCLE = ',A3,' CYCLE MUST EQUAL TP,
     #TX, PX, PS, PH',//,5X,'FREON TERMINATED')
9010  FORMAT(1H ,4X,'***ERROR*** TEMPERATURE AND PRESSURE ARE NOT
     #INDEPENDENT UNDER THE SATURATION DOME',//,5X,'FREON TERMINATED')
9020  FORMAT(1H ,4X,'***ERROR*** A SATURATION STATE DOES NOT EXIST
     #FOR TEMPERATURES ABOVE THE CRITICAL TEMPERATURE',F10.3,'DEG.F',
     #//,5X,    'FREON TERMINATED')
9030  FORMAT(1H ,4X,'***ERROR*** A SATURATION STATE DOES NOT EXIST FOR
     #PRESSURES ABOVE THE CRITICAL PRESSURE',F10.3,'PSIA',//,5X,
     #'FREON TERMINATED')
9040  FORMAT(1H ,4X,'THE MARTIN-HOU EQUATION OF STATE IS NOT VALID IN
     #THIS REGION,2.E. P>PC AND S;SC',//,5X,'FREON TERMINATED')
9050  FORMAT(1H ,4X,'THE MARTIN-HOU EQUATION OF STATE IS NOT VALID IN
     #THIS REGION,2.E. P>PC AND H;HC',//,5X,'FREON TERMINATED')
9060  FORMAT(1H ,4X,'***ERROR*** THE FLUID ',A6,' CAN NOT BE EVALUATED
     #USING THE SUBROUTINE FREON',//,5X,'FREON TERMINATED')
9070  FORMAT(1H ,4X,'***ERROR*** A QUALITY OF ',F6.3,'IS NOT ALLOWED',
     #//,5X,'FREON TERMINATED')
      END
C
      _____
      SUBROUTINE VPEQM(P1,T,M)
C  THIS SUBROUTINE CALCULATES THE SATURATION PRESSURE OR TEMPERATURE
C  GIVEN THE OTHER
      PARAMETER (M2=6)
      COMMON/FREON1/Q(4,12),TTOLER,BTOLER,LIMIT,DERROR,NTYPE
      REAL LOGP
      TC=Q(4,3)+Q(1,11)
      IF(M.EQ.1) GOTO 100
      T1=ABS(Q(2,1)/(ALOG10(P1)-Q(1,1)))
      TMISS=(T1-T)/T1
      IF(ABS(TMISS).GT..2D+00) T=T1
100   DO 105 ITR=1,LIMIT
      T2=T*T
      T3=T*T2
      FT=Q(2,2)-T
      IF(FT.LT..1E-20) FT=1.0
      LOGP=Q(1,1)+Q(2,1)/T+Q(3,1)*ALOG10(T)+Q(4,1)*T+Q(1,2)*FT/T*
     #ALOG10(FT)
      P2=10.0**LOGP
      IF(M.EQ.1) P1=P2
      DELP=P1-P2
      ERROR=DELP/P1
         IF(ABS(ERROR).LT..1D-06) GOTO 110
```

```
      IF(P2/P1.LT.TTOLER.AND.P2/P1.GT.BTOLER) RETURN
      CALL DRVPT(DPDT,P2,T,D2PDT2)
      DELT=DELP/DPDT
      T=T+DELT
      IF(T.GT.TC) T=TC
  105 CONTINUE
C     WRITE(M2,115) LIMIT,P1,P2
  110 RETURN
  115 FORMAT(1H ,4X,'***VPEQM FAILED TO CONVERGE IN',I6,'ITERATIONS',
     # /,'DESIRED PRESSURE=',F10.3,'CALCULATED PRESSURE=',F10.3)
      END
C     _____
      SUBROUTINE VOLUME(T,P,V)
C THIS SUBROUTINE FINDS THE VAPOR DENSITY BY USE OF THE NEWTON-
C RAPHSON ITERATION METHOD, GIVEN PRESSURE AND TEMPERATURE.
      PARAMETER (M2=6)
      COMMON/FREON1/Q(4,12),TTOLER,BTOLER,LIMIT,DERROR,NTYPE
      V=Q(2,3)*T/P
      VLAST=V
      CALL EOS(PCAL,T,V,DPDT,DPDV,DPDVDT,DP2DT2)
      DO 1000 I=1,LIMIT
      V=VLAST-((PCAL-P)/DPDV)
      IF(V.LE.0.0) V=VLAST/10.0
      CALL EOS(PCAL,T,V,DPDT,DPDV,DPDVDT,DP2DT2)
      IF(PCAL/P.LT.TTOLER.AND.PCAL/P.GT.BTOLER.OR.ABS(V-VLAST).LT.
     #   1.0E-10) RETURN
      VLAST=V
 1000 CONTINUE
C     WRITE(M2,9000) LIMIT
 9000 FORMAT(11X,'***VOLUME FAILED TO CONVERGE IN ',I5,' ITERATIONS')
      RETURN
      END
C     _____
      SUBROUTINE ENTHAL(P,T,V,H,DHDT,DHDV)
      COMMON/FREON1/Q(4,12),TTOLER,BTOLER,LIMIT,DERROR,NTYPE
      C=0.185053
      T2=T*T
      T3=T2*T
      T4=T3*T
      VMB=V-Q(3,3)
      VMB2=VMB*VMB
      VMB3=VMB2*VMB
      VMB4=VMB3*VMB
      VMB5=VMB4*VMB
      EKIT=-Q(2,12)*T/(Q(4,3)+Q(1,11))
      EKIT=EXP(EKIT)
      EKA=Q(3,12)*V
      IF(EKA.GT.30.0) GOTO 105
      IF(ABS(EKA).LE.DERROR) GOTO 105
      EKA=EXP(EKA)
      IF(ABS(Q(1,12)).LE.DERROR) GOTO 100
      PART=Q(1,12)*ALOG((Q(1,12)*EKA+1.0)/(Q(1,12)*EKA))
      GOTO 110
  100 PART=0.0
      GOTO 110
  105 EKA=0.0
      RX=0.0
      RZ=0.0
      PART=0.0
      TERMA=0.0
      TERMB=0.0
      GOTO 115
```

```
110 RX=Q(2,8)/Q(3,12)*(1.0/EKA-PART)
    RZ=Q(4,8)/(Q(3,12)*EKA)-(Q(4,8)*PART/Q(3,12))
    TERMA=Q(2,8)*(-1.0/EKA+Q(1,12)/(Q(1,12)*EKA+1.0))
    TERMB=Q(4,8)/EKA
115 CALL EOS(P,T,V,DPDT,DPDV,DPDVDT,D2PDT2)
    H1=Q(1,9)*T+Q(2,9)*T2/2.0+Q(3,9)*T3/3.0+Q(4,9)*T4/4.0-
   #  Q(1,10)/T+C*P*V
    H2=C*(Q(2,4)/VMB+Q(2,5)/(2.0*VMB2)+Q(2,6)/(3.0*VMB3)+Q(2,7)
   #   /(4.0*VMB4)+RX)
    H3=C*(Q(4,4)/VMB+Q(4,5)/(2.0*VMB2)+Q(4,7)/(4.0*VMB4)+Q(4,6)
   #   /(3.0*VMB3)+RZ)*(1.0+Q(2,12)*T/(Q(4,3)+Q(1,11)))*EKIT+Q(2,10)
    H=H1+H2+H3
    TC=Q(4,3)+Q(1,11)
    PART1=Q(1,9)+Q(2,9)*T+Q(3,9)*T2+Q(4,9)*T3+Q(1,10)/T2+C*DPDT*V
    PART2=Q(4,4)/VMB+Q(4,5)/(2.0*VMB2)+Q(4,6)/(3.0*VMB3)+Q(4,7)/(4.0*
   #    VMB4)+RZ
    PART 2=-C*EKIT*Q(2,12)**2*T/TC**2*PART2
    DHDT=PART1+PART2
    PART1=C*DPDV*V+C*P+C*(-Q(2,4)/VMB2-Q(2,5)/VMB3-Q(2,6)/VMB4-
   #Q(2,7)/VMB5+TERMA)
    PART2=-Q(4,4)/VMB2-Q(4,5)/VMB3-Q(4,6)/VMB4-Q(4,7)/VMB5-TERMB
   #    +Q(4,8)*Q(1,12)/(Q(1,12)*EKA+1.0)
    PART2=C*EKIT*(1.0+Q(1,12)*T/TC)*PART2
    DHDV=PART1+PART2
    RETURN
    END
```

C

```
    SUBROUTINE ENTROP(T,V,S,DSDT,DSDV)
C   THIS SUBROUTINE COMPUTES THE ENTROPY OF THE VAPOR.
    COMMON/FREON1/Q(4,12),TTOLER,BTOLER,LIMIT,DERROR,NTYPE
    C=0.185053
    VMB=V-Q(3,3)
    VMB2=VMB*VMB
    VMB3=VMB2*VMB
    VMB4=VMB3*VMB
    VMB5=VMB4*VMB
    EKA=Q(3,12)*V
    IF(ABS(EKA).GT.30.0) GOTO 100
    IF(ABS(EKA).LT.DERROR) GOTO 100
    IF(ABS(Q(1,12)).LE.DERROR) GOTO 100
    EKA=EXP(EKA)
    PART=Q(1,12)*ALOG((Q(1,12)*EKA+1.0)/(Q(1,12)*EKA))
    GOTO 105
100 RX=0.0
    RZ=0.0
    EKA=0.0
    PART=0.0
    TERMA=0.0
    TERMB=0.0
    GOTO 110
105 RX=Q(3,8)/Q(3,12)*(1.0/EKA-PART)
    RZ=Q(4,8)/(Q(3,12)*EKA)-(Q(4,8)/Q(3,12)*PART)
    TERMA=Q(3,8)*(-1.0/EKA+Q(1,12)/(Q(1,12)*EKA+1.0))
    TERMB=Q(4,8)/EKA
110 G=Q(4,4)/VMB+Q(4,5)/(2.0*VMB2)+Q(4,7)/(4.0*VMB4)+Q(4,6)/
   #    (3.0*VMB3)+RZ
    T2=T*T
    T3=T2*T
    EKIT=-Q(2,12)*T/(Q(4,3)+Q(1,11))
    IF(ABS(EKIT).GT.30.0) GOTO 115
    EKIT = EXP(EKIT)
    GOTO 120
```

```
  115 EKIT = 0.0
  120 ZZ=Q(2,12)**2.0/(Q(4,3)+Q(1,11))**2.0*EKIT
      S1=Q(1,9)*ALOG(T)+Q(2,9)*T+Q(3,9)*T2/2.0+Q(4,9)*T3/3.0-Q(1,10)
     #   /(2.0*T2)
      S2=C*Q(2,3)*ALOG(VMB)
      S3=C*(Q(3,4)/VMB+Q(3,5)/(2.0*VMB2)+Q(3,6)/(3.0*VMB3)+Q(3,7)/
     #   (4.0*VMB4)+RX)
      S4=C*(Q(2,12)/(Q(4,3)+Q(1,11))*EKIT)*(Q(4,4)/VMB+Q(4,5)/
     #(2.0*VMB2)+Q(4,6)/(3.0*VMB3)+Q(4,7)/(4.0*VMB4)+RZ)+Q(3,10)
      S=S1+S2+S3+S4
      DSDT=Q(1,9)/T+Q(2,9)+Q(3,9)*T+Q(4,9)*T2+Q(1,10)/T3-C*G*ZZ
      TC=Q(4,3)+Q(1,11)
      PART1=C*Q(2,3)/VMB-C*(-Q(3,4)/VMB2-Q(3,5)/VMB3-Q(3,6)/VMB4-
     #Q(3,7)/VMB5+TERMA)
      PART2=C*Q(2,12)*EKIT/TC*(-Q(4,4)/VMB2-Q(4,5)/VMB3-Q(4,6)/VMB4
     #     -Q(4,7)/VMB5-TERMB+Q(4,8)*Q(1,12)/(Q(1,12)*EKA+1.0))
      DSDV=PART1+PART2
  130 RETURN
      END
C     _____              -
      SUBROUTINE PRINTF(T,P,QUAL,V,H,S,VV,HV,SV,VL,HL,SL,FTYPE,NPRIN)
C THIS SUBROUTINE PRINTS THE RESULTS OF ROUTINE FREON
      CHARACTER*6 FTYPE
      PARAMETER (M2=6)
      COMMON/FREON1/Q(4,12),TTOLER,BTOLER,LIMIT,DERROR,NTYPE
      T=T-Q(1,11)
      IF(NPRIN.EQ.0) RETURN
C     WRITE(M2,9000) FTYPE
C     WRITE(M2,9010) T,P
      IF(QUAL.LE.1.0.AND.QUAL.GE.0.0) GOTO 3280
C     IF(QUAL.GT.1.0) WRITE(M2,9020)
C     IF(QUAL.LT.0.0) WRITE(M2,9030)
      GOTO 3370
 3280    continue
C        WRITE(M2,9040) QUAL
C     WRITE(M2,9050)
C     WRITE(M2,9070) HV,HL
C     WRITE(M2,9080) SV,SL
C     WRITE(M2,9060) VV,VL
 3370    continue
C        WRITE(M2,9090)
C     WRITE(M2,9070) H
C     WRITE(M2,9080) S
C     WRITE(M2,9060) V
 9000 FORMAT(1H1,4X,'***THERMODYNAMIC PROPERTIES OF ',A6,' USING
     #    MARTIN-HOU EQUATION OF STATE***')
 9010 FORMAT(1H ,4X,'TEMPERATURE = ',F7.1,'DEG.F',/,5X,'PRESSURE    =
     # ',F10.5,'PSIA')
 9020 FORMAT(1H ,4X,'SUPERHEATED VAPOR',//////)
 9030 FORMAT(1H ,4X,'COMPRESSED LIQUID-APPROXIMATED BY SATURATED
     # LIQUID',//////)
 9040 FORMAT(1H ,4X,'SATURATED LIQUID-VAPOR EQUILIBRIUM',//,5X,'QUALITY
     # = ',F6.4)
 9050 FORMAT(1H ,//,35X,'SATURATED',8X,'SATURATED',//,35X,'VAPOR',12X,
     1     'LIQUID',/,5X,60('#'))
 9060 FORMAT(1H ,4X,'SPECIFIC VOLUME (CU.FT/LBM)',5X,F9.4,8X,F9.4,/////
     1     /)
 9070 FORMAT(1H ,4X,'ENTHALPY',8X,'(BTU/LBM)',5X,F9.3,8X,F9.3)
 9080 FORMAT(1H ,4X,'ENTROPY',9X,'(BTU/LBM-R)',5X,F9.6,8X,F9.6)
 9090 FORMAT(1H ,//////)
      RETURN
      END
```

```
C   _____
        SUBROUTINE DRVPT(DPDT,P,T,D2PDT2)
        COMMON/FREON1/Q(4,12),TTOLER,BTOLER,LIMIT,DERROR,NTYPE
        T2=T*T
        T3=T2*T
        FT=Q(2,2)-T
        IF(FT.LT.0.01) FT=1.0
        XX=ALOG(10.0)
        DPDT=P*((-XX*(Q(2,1)+Q(1,2)*Q(2,2)*ALOG10(FT)))/T2+(Q(3,1)-
       #Q(1,2))/T+Q(4,1)*XX)
        D2PDT2=P*(2.0*XX*(Q(2,1)+Q(1,2)*Q(2,2)*ALOG10(FT))/T3+
       # XX/T2*(0.43429448/FT)+(Q(3,1)-Q(1,2))/T2)
        RETURN
        END
C   _____
        SUBROUTINE FLQDEN(VL,TR,DVLDT)
C   THIS SUBROUTINE COMPUTES THE SATURATED LIQUID SPECIFIC VOLUME GIVEN
C   TEMPERATURE USING ONE OF THREE EQUATONS
        COMMON/FREON1/Q(4,12),TTOLER,BTOLER,LIMIT,DERROR,NTYPE
        TC=Q(4,3)+Q(1,11)
100     GOTO (200,300,400),NTYPE
200     P1=1.0/3.0
        P2=2.0/3.0
        P3=4.0/3.0
        T=1.0-TR/TC
        DL=Q(1,4)+Q(1,5)*T**P1+Q(1,6)*T**P2+Q(1,7)*T**P3
        VL=1.0/DL
        T3=3.0*TC
        DVLDT=VL**2*(Q(1,5)/(T3*T**P2)+2.0*Q(1,6)/(T3*T**P1)+Q(1,7)/TC
       #      +4.0*Q(1,8)/(T3*T**P1))
        RETURN
300     P1=1.0
        P2=1.0/2.0
        P3=1.0/3.0
        P4=2.0/3.0
        T=TC-TR
        DL=Q(1,4)+Q(1,5)*T**P1+Q(1,6)*T**P2+Q(1,7)*T**P3+Q(1,8)*T**2
        VL=1.0/DL
        DVLDT=VL**2*(Q(1,5)+Q(1,6)/(2.0*T**P2)+Q(1,7)/(3.0*T**P4)+2.0*
       #      Q(1,8)*T)
        RETURN
400     DL=Q(1,4)+Q(1,5)*TR+Q(1,6)*TR**2
        VL=1.0/DL
        DVLDT=VL**2*(-Q(1,5)-Q(1,6)*2.0*TR)
        RETURN
        END
C   _____
        SUBROUTINE SATN(PSIA,T,V,HV,SV,HL,SL,VL)
C   THIS SUBROUTINE COMPUTES THE SATURATED VAPOR-LIQUID PROPERTIES GIVEN
C   TEMPERATURE AND   SPECIFIC VOLUME
        COMMON/FREON1/Q(4,12),TTOLER,BTOLER,LIMIT,DERROR,NTYPE
        CALL FLQDEN(VL,T,DVLDT)
        RJ=0.185053
        CALL ENTHAL(PSIA,T,V,H,DHDT,DHDV)
        CALL DRVPT(DPSDT,PSIA,T,DPSDT2)
        DELTH=RJ*DPSDT*(V-VL)*T
        HL=H-DELTH
        CALL ENTROP(T,V,S,DSDT,DSDV)
        SL=S-DELTH/T
        VV=V
        HV=H
        SV=S
```

```
      RETURN
      END
C  _____
      SUBROUTINE SFIND(T,P,V,S)
C THIS SUBROUTINE FINDS TEMPERATURE AND DENSITY GIVEN PRESSURE
C  AND ENTROPY
C FOR SUPERHEATED VAPOR STATES.
      PARAMETER (M2=6)
      COMMON/FREON1/Q(4,12),TTOLER,BTOLER,LIMIT,DERROR,NTYPE
      VLAST=V
      TLAST=T
      CALL EOS(PCAL,T,V,DPDT,DPDV,DPDVDT,D2PDT2)
      CALL ENTROP(T,V,SCAL,DSDT,DSDV)
      DO 1000 I=1,LIMIT
      XJACOB=DPDV*DSDT-DPDT*DSDV
      V=VLAST-((PCAL-P)*DSDT-(SCAL-S)*DPDT)/XJACOB
      T=TLAST-((SCAL-S)*DPDV-(PCAL-P)*DSDV)/XJACOB
      IF(T.LE.0.0) T=TLAST/10.0
      IF(V.LE.0.0) V=VLAST/10.0
      CALL ENTROP(T,V,SCAL,DSDT,DSDV)
      CALL EOS(PCAL,T,V,DPDT,DPDV,DPDVDT,D2PDT2)
      IF(PCAL/P.LT.TTOLER.AND.PCAL/P.GT.BTOLER.AND.SCAL/S.LT.
     #   TTOLER.AND.SCAL/S.GT.BTOLER) GOTO 1050
      IF(ABS(T-TLAST).LT.1.0E-04.AND.ABS(V-VLAST).LT.1.0E-07) GOTO 1050
      VLAST=V
      TLAST=T
 1000 CONTINUE
C     WRITE(M2,9000) LIMIT
 1050 RETURN
 9000 FORMAT(' ',10X,'***SFIND FAILED TO CONVERGE IN ',I5,
     #' ITERATIONS')
      END
C  _____
      SUBROUTINE COMPS(P,T,V,S,VL)
C THIS SUBROUTINE FINDS THE TEMPERATURE AND DENSITY GIVEN
C PRESSURE AND ENTROPY FOR COMPRESSED LIQUID STATES.
      PARAMETER (M2=6)
      COMMON/FREON1/Q(4,12),TTOLER,BTOLER,LIMIT,DERROR,NTYPE
      RJ=0.185053
      VLAST=V
      TLAST=T
      CALL EOS(PCAL,T,V,DPDT,DPDV,DPDVDT,D2PDT2)
      CALL VPEQM(PSAT,T,1)
      CALL ENTROP(T,V,SCAL,DSDT,DSDV)
      CALL DRVPT(DPSDT,PSAT,T,DPSDT2)
      CALL FLQDEN(VL,T,DVLDT)
      DO 1000 I=1,LIMIT
      FP=PCAL-PSAT
      DFPDT=DPDT-DPSDT
      FS=SCAL-RJ*DPSDT*(V-VL)-S
      DFSDT=DSDT-RJ*DPSDT2*(V-VL)+RJ*DPSDT*DVLDT
      DFSDV=DSDV-RJ*DPSDT
      XJACOB=DPDV*DFSDT-DFPDT*DFSDV
      V=VLAST-(FP*DFSDT-FS*DFPDT)/XJACOB
      T=TLAST-(FS*DPDV-FP*DFSDV)/XJACOB
      IF(T.LE.0.0) T=TLAST/10.0
      IF(V.LE.0.0) V=VLAST/10.0
      CALL EOS(PCAL,T,V,DPDT,DPDV,DPDVDT,D2PDT2)
      CALL VPEQM(PSAT,T,1)
      CALL ENTROP(T,V,SCAL,DSDT,DSDV)
      CALL DRVPT(DPSDT,PSAT,T,DPSDT2)
      CALL FLQDEN(VL,T,DVLDT)
```

```
          SL=SCAL-RJ*(V-VL)*DPSDT
          IF(PCAL/PSAT.LT.TTOLER.AND.PCAL/PSAT.GT.BTOLER.AND.SL/S.LT.
     #    TTOLER.AND.SL/S.GT.BTOLER) GOTO 1050
          IF(ABS(T-TLAST).LT.1.0E-04.AND.ABS(V-VLAST).LT.1.0E-07) GOTO 1050
          VLAST=V
          TLAST=T
 1000 CONTINUE
C         WRITE(M2,9000) LIMIT
 1050 P=PCAL
          RETURN
 9000 FORMAT(' ',10X,'***COMPS FAILED TO CONVERGE IN ',I5,
     #' ITERATIONS')
          END
C     _____
          SUBROUTINE HFIND(T,P,V,H)
C THIS SUBROUTINE FINS TEMPERATURE AND DENSITY GIVEN PRESSURE
C AND ENTHALPY FOR SUPERHEATED VAPOR STATES.
          PARAMETER (M2=6)
          COMMON/FREON1/Q(4,12),TTOLER,BTOLER,LIMIT,DERROR,NTYPE
          VLAST=V
          TLAST=T
          CALL EOS(PCAL,T,V,DPDT,DPDV,DPDVDT,DP2DT2)
          CALL ENTHAL(PCAL,T,V,HCAL,DHDT,DHDV)
          DO 1000 I=1,LIMIT
          XJACOB=DPDV*DHDT-DPDT*DHDV
          V=VLAST-((PCAL-P)*DHDT-(HCAL-H)*DPDT)/XJACOB
          T=TLAST-((HCAL-H)*DPDV-(PCAL-P)*DHDV)/XJACOB
          IF(T.LE.0.0) T=TLAST/10.0
          IF(V.LE.0.0) V=VLAST/10.0
          CALL EOS(PCAL,T,V,DPDT,DPDV,DPDVDT,DP2DT2)
          CALL ENTHAL(PCAL,T,V,HCAL,DHDT,DHDV)
          IF(PCAL/P.LT.TTOLER.AND.PCAL/P.GT.TTOLER.AND.HCAL/H.LT.
     #    TTOLER.AND.HCAL/H.GT.BTOLER) GOTO 1050
          IF(ABS(T-TLAST).LT.1.0E-04.AND.ABS(V-VLAST).LT.1.0E-07) GOTO 1050
          VLAST=V
          TLAST=T
 1000 CONTINUE
C         WRITE(M2,9000) LIMIT
 1050 RETURN
 9000 FORMAT(' ',10X,'HFIND FAILED TO CONVERGE IN ',I5,' ITERATIONS')
          END
C     _____
          SUBROUTINE COMPH(P,T,V,H,VL)
C THIS SUBROUTINE FINS THE TERMPERATURE AND DENSITY GIVEN
C PRESSURE AND ENTHALPY FOR COMPRESSED LIQUID STATES
          PARAMETER (M2=6)
          COMMON/FREON1/Q(4,12),TTOLER,BTOLER,LIMIT,DERROR,NTYPE
          RJ=0.185053
          VLAST=V
          TLAST=T
          CALL EOS(PCAL,T,V,DPDT,DPDV,DPDVDT,DP2DT2)
          CALL VPEQM(PSAT,T,1)
          CALL ENTHAL(PCAL,T,V,HCAL,DHDT,DHDV)
          CALL DRVPT(DPSDT,PSAT,T,DPSDT2)
          CALL FLQDEN(VL,T,DVLDT)
          DO 1000 I=1,LIMIT
          FP=PCAL-PSAT
          DFPDT=DPDT-DPSDT
          FH=HCAL-RJ*DPSDT*(V-VL)*T-H
          DFHDT=DHDT-RJ*(DPSDT2*(V-VL)*T-DPSDT*DVLDT*T+DPSDT*(V-VL))
          DFHDV=DHDV-RJ*DPSDT*T
          XJACOB=DPDV*DFHDT-DFPDT*DFHDV
```

```
      V=VLAST-(FP*DFHDT-FH*DFPDT)/XJACOB
      T=TLAST-(FH*DPDV-FP*DFHDV)/XJACOB
      IF(T.LE.0.0) T=TLAST/10.0
      IF(V.LE.0.0) V=VLAST/10.0
      CALL EOS(PCAL,T,V,DPDT,DPDV,DPDVDT,DP2DT2)
      CALL VPEQM(PSAT,T,1)
      CALL ENTHAL(PCAL,T,V,HCAL,DHDT,DHDV)
      CALL DRVPT(DPSDT,PSAT,T,DPSDT2)
      CALL FLQDEN(VL,T,DVLDT)
      HL=HCAL-RJ*DPSDT*(V-VL)*T
      IF(PCAL/PSAT.LT.TTOLER.AND.PCAL/PSAT.GT.BTOLER.AND.HL/H.LT.
     #  TTOLER.AND.HL/H.GT.BTOLER) GOTO 1050
      IF(ABS(T-TLAST).LT.1.0E-04.AND.ABS(V-VLAST).LT.1.0E-07) GOTO 1050
      VLAST=V
      TLAST=T
 1000 CONTINUE
c      WRITE(M2,9000) LIMIT
 1050 P=PCAL
      RETURN
 9000 FORMAT(' ',10X,'***COMPH FAILED TO CONVERGE IN ',I5,
     #' ITERATIONS')
      END
c
     _____
      SUBROUTINE EOS(P,T,V,DPDT,DPDV,DPDVDT,D2PDT2)
C THIS SUBROUTINE CALCULATES THE PRESSURE FOR VAPRO STATES AND
C ITS DERIVATIVES GIVEN TEMPERATURE AND DENSITY
      COMMON/FREON1/Q(4,12),TTOLER,BTOLER,LIMIT,DERROR,NTYPE
      DIMENSION TERM(6),PART(7)
      DPDV=0.0
      P1=0.0
      VMB=V-Q(3,3)
      EKIT=-Q(2,12)*T/(Q(4,3)+Q(1,11))
      EKIT=EXP(EKIT)
      EKA=Q(3,12)*V
      EKA2=2.00*Q(3,12)*V
      IF(ABS(EKA).LE.DERROR) GOTO 105
      IF(ABS(EKA).GT.30.0) GOTO 105
      EKA=EXP(EKA)
      EKA2=EXP(EKA2)
      GOTO 115
  105 EKA=0.0
      EKA2=0.0
  115 TERM(1) = Q(2,3)*T/VMB
      DO 125 I=2,5
      TERM(I)=(Q(2,I+2)+Q(3,I+2)*T+Q(4,I+2)*EKIT)/VMB**I
  125 P1=P1+TERM(I)
      IF(ABS(EKA).LE.DERROR) TERM(6)=0.0
      IF(ABS(EKA).LE.DERROR) GOTO 120
      TERM(6)=(Q(2,8)+Q(3,8)*T+Q(4,8)*EKIT)/(EKA*(1.0+Q(1,12)*EKA))
  120 P1=P1+TERM(1) +TERM(6)
      P=P1
  140 PART(1)=Q(2,3)*T/VMB**2
      DO 150 I=2,5
      PART(I)=FLOAT(I)*(Q(2,I+2)+Q(3,I+2)*T+Q(4,I+2)*EKIT)/VMB**(I+1)
  150 DPDV=DPDV+PART(I)
      IF(ABS(EKA).LE.DERROR) PART(6) =0.0
      IF(ABS(EKA).LE.DERROR) GOTO 145
      IF(EKA2.GT.30.0) EKA2=0.0
      XMESS=(Q(3,12)*EKA+2.0*Q(3,12)*Q(1,12)*EKA2)/((EKA+Q(1,12)*
     # EKA2)**2)
      XMESS=-XMESS
      PART(6)=(Q(2,8)+Q(3,8)*T+Q(4,8)*EKIT)*XMESS
```

```
145 DPDV=-(DPDV+PART(1) + PART(6))
    VMB2=VMB*VMB
    VMB3=VMB2*VMB
    VMB4=VMB2**2
    VMB5=VMB4*VMB
    VMB6=VMB3*VMB3
    TC=Q(4,3)+Q(1,11)
    CK2=Q(4,4)*Q(2,12)/TC
    CK3=Q(4,5)*Q(2,12)/TC
    CK4=Q(4,6)*Q(2,12)/TC
    CK5=Q(4,7)*Q(2,12)/TC
    CK6=Q(4,8)*Q(2,12)/TC
    EKA=Q(3,12)*V
    IF(ABS(EKA).LE.DERROR) GOTO 100
    IF(EKA.GT.30.0) GOTO 100
    EKA=EXP(EKA)
    TERMA=(Q(3,8)-CK6*EKIT)/(EKA*(1.0+Q(1,12)*EKA))
    TERMB=Q(4,8)/(EKA*(1.0+Q(1,12)*EKA))
    Z6=Q(3,12)*(1.0+2.0*Q(1,12)*EKA)/(EKA*(1.0+Q(1,12)*EKA))
    GOTO 180
100 TERMA=0.0
    TERMB=0.0
    Z6=0.0
    EKA=0.0
180 DPDT=Q(2,3)/VMB+(Q(3,4)-CK2*EKIT)/VMB2+(Q(3,5)-CK3*EKIT)/VMB3+
   #     (Q(3,6)-CK4*EKIT)/VMB4+(Q(3,7)-CK5*EKIT)/VMB5+TERMA
    D2PDT2=Q(2,12)**2*EKIT/TC**2*(Q(4,4)/VMB2+Q(4,5)/VMB3+Q(4,6)/
   #VMB4+Q(4,7)/VMB5+TERMB)
    Z1=Q(3,4)-Q(2,12)*Q(4,4)*EKIT/TC
    Z2=Q(3,5)-Q(2,12)*Q(4,5)*EKIT/TC
    Z3=Q(3,6)-Q(2,12)*Q(4,6)*EKIT/TC
    Z4=Q(3,7)-Q(2,12)*Q(4,7)*EKIT/TC
    Z5=Q(3,8)-Q(2,12)*Q(4,8)*EKIT/TC
    DPDVDT=-Q(3,2)/VMB2-2.0*Z1/VMB3-3.0*Z2/VMB4-4.0*Z3/VMB5-5.0*Z4/
   #VMB6-Z5*Z6
175 RETURN
    END
C   _____
    SUBROUTINE SIFREON (CYCLE,FGIVEN,SGIVEN,FTYPE,H,S,V,TR,P,
   #     HV,SV,VV,HL,SL,VL,QUAL,NPRT)
    IMPLICIT REAL(L)
    INTEGER CALLIN
    CHARACTER CYCLE*2,FTYPE*6
    IF(CYCLE.EQ.'TP') THEN
    FGIVEN=FGIVEN*1.8+32.
    SGIVEN=.145037743897283*SGIVEN
    ELSEIF(CYCLE.EQ.'TX') THEN
    FGIVEN=FGIVEN*1.8+32.
    ELSEIF(CYCLE.EQ.'PS') THEN
    FGIVEN=.145037743897283*FGIVEN
    SGIVEN=SGIVEN/4.1868
    ELSEIF(CYCLE.EQ.'PH') THEN
    FGIVEN=.145037743897283*FGIVEN
    SGIVEN=SGIVEN/2.326
    ELSEIF(CYCLE.EQ.'PX') THEN
    FGIVEN=FGIVEN*.145037743897283
    ELSEIF(CYCLE.EQ.'TV') THEN
    FGIVEN=FGIVEN*1.8+32.
    SGIVEN=SGIVEN*0.01602
    ELSE
    PRINT*,'WRONG CYCLE VALUE IS GIVEN'
    RETURN
```

```
ENDIF
CALL FREON(CYCLE,FGIVEN,SGIVEN,FTYPE,H,S,V,TR,P,
#     HV,SV,VV,HL,SL,VL,QUAL,NPRT)
S=S*4.1868
H=H*2.326
V=V*0.0624219
TR=(TR-32.)/1.8
P=P/.145037743897283
SL=SL*4.1868
HL=HL*2.326
VL=VL*0.0624219
SV=SV*4.1868
HV=HV*2.326
VV=VV*0.0624219
RETURN
END
```

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