A comparison of thermal storage models with a solar electric generation system using Trnsys

Jade Gaal
University of Nevada, Las Vegas

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A COMPARISON OF THERMAL STORAGE MODELS
WITH A SOLAR ELECTRIC GENERATION SYSTEM USING TRNSYS

by

Jade Gaal
Bachelor of Science
University of Nevada, Las Vegas
2001

A thesis submitted in partial fulfillment of the requirements for the

Master of Science Degree in Mechanical Engineering
Department of Mechanical Engineering
Howard R. Hughes College of Engineering

Graduate College
University of Nevada, Las Vegas
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Thesis Approval
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Jade Gaal

Entitled

A Comparison of Thermal Storage Models with a Solar Electric Generation System using TRNSYS

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Examination Committee Chair

Dean of the Graduate College

Examination Committee Member

Graduate College Faculty Representative
ABSTRACT

A Comparison of Thermal Storage Models with a Solar Electric Generation System using TRNSYS

by

Jade Braithwaite

Dr. Robert Boehm, Committee Chair
Professor of Mechanical Engineering
University of Nevada, Las Vegas

Two new component types were developed for the transient simulation program TRNSYS with IISiBat that models three different types of sensible thermal storages for analysis with use in a solar electric generating system (SEGS) simulation. One component containing a fully mixed, stratified and a plug flow tank model has been developed such that the inputs and parameter specifications are similar so that all three models could be easily placed into one component type. A single, cylindrical direct storage tank with one inlet and one outlet that evaluates fluid properties as a function of temperature is representative for all three models. The second component is a storage controller that passes along pertinent charging, dwell or discharging information to the storage and integrates the storage into a given SEGS model.

Results are provided for each storage tank integrated in a SEGS VI simulation model for temperature distribution and power generation.
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<tr>
<td>$A_c$</td>
<td>Cross sectional area of tank</td>
</tr>
<tr>
<td>$C_{p_{\text{bot}}}$</td>
<td>Specific heat for the bottom node</td>
</tr>
<tr>
<td>$C_{p_i}$</td>
<td>Specific heat for the $i^{\text{th}}$ node</td>
</tr>
<tr>
<td>$C_{p_{i+1}}$</td>
<td>Specific heat for the node below the $i^{\text{th}}$ node</td>
</tr>
<tr>
<td>$C_{p_{i-1}}$</td>
<td>Specific heat for the node above the $i^{\text{th}}$ node</td>
</tr>
<tr>
<td>$C_p$</td>
<td>Specific heat</td>
</tr>
<tr>
<td>$C_{p_{\text{in}}}$</td>
<td>Specific heat of incoming flow into storage</td>
</tr>
<tr>
<td>$C_{p_{\text{tank}}}$</td>
<td>Specific heat in storage</td>
</tr>
<tr>
<td>$C_{p_{\text{top}}}$</td>
<td>Specific heat in top node</td>
</tr>
<tr>
<td>$\Delta E$</td>
<td>Change in energy</td>
</tr>
<tr>
<td>$E_{\text{in}}$</td>
<td>Energy in</td>
</tr>
<tr>
<td>$E_{\text{out}}$</td>
<td>Energy out</td>
</tr>
<tr>
<td>$k$</td>
<td>Thermal conductivity</td>
</tr>
<tr>
<td>$k_{\text{bot}}$</td>
<td>Thermal conductivity of bottom</td>
</tr>
<tr>
<td>$k_{i+1}$</td>
<td>Thermal conductivity of the node below the $i^{\text{th}}$ node</td>
</tr>
<tr>
<td>$k_{i-1}$</td>
<td>Thermal conductivity of the node above the $i^{\text{th}}$ node</td>
</tr>
<tr>
<td>$k_{\text{top}}$</td>
<td>Thermal conductivity of top node</td>
</tr>
<tr>
<td>$M$</td>
<td>Mass flow rate into storage tank</td>
</tr>
<tr>
<td>$M_{\text{bot}}$</td>
<td>Mass in bottom node</td>
</tr>
<tr>
<td>$M_{\text{charge}}$</td>
<td>Mass flow rate to storage for charging</td>
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\( M_i \)  Mass in the \( i^{th} \) node

\( M_{\text{tank}} \)  Mass in storage tank

\( M_{\text{top}} \)  Mass in top node

\( M_{\text{trough}} \)  Mass flow rate from trough

\( P_{\text{des}} \)  User specified minimum power (desired power)

\( P_{\text{act}} \)  Actual power generation

\( T \)  Temperature

\( T_{\text{bot}} \)  Temperature for the bottom node

\( T_{\text{in}} \)  Temperature of incoming flow (either charging or discharging)

\( T_{i+1} \)  Temperature of the node below the \( i^{th} \) node

\( T_{i-1} \)  Temperature of the node above the \( i^{th} \) node

\( T^{-1} \)  Temperature at last time step

\( T_{\text{new}} \)  Temperature at next time step

\( T_{\text{tank}} \)  Temperature in storage tank

\( T_{\text{top}} \)  Temperature in top node

\( t \)  Time

\( \Delta t \)  Time step

\( \Delta x \)  Distance between nodes

\( \rho \)  Density
CHAPTER 1

INTRODUCTION

Solar electric generating systems (SEGS) utilizing parabolic trough technology is fast becoming one of the most economical methods for renewable energy. Compared to conventional power generation systems however, the initial cost, operation and maintenance of such a system is still considered to be too high for many investors. This is because most SEGS are only able to operate during times of high solar radiation, which not only limits the amount of power generation but also the time of distribution of the power. Many locations have high demands for electricity during periods other than the peak time of solar energy. This causes a misalignment between the demand and power curve which creates a higher levelized energy cost (LEC) for a SEGS plant [1].

Implementation of a thermal storage system within a SEGS would allow for longer operating periods; shifting of the power curve to meet a later demand as well as providing a more evenly distributed power generation output during periods of transient events. Because the cost of electricity is the highest during peak demand periods, a SEGS plant operating with storage would result in more revenue creating a lower LEC as well as improved plant efficiency [1]. However only a handful of solar electric generating systems have been designed with thermal storage. Much of this is from an economical standpoint in which
investors and developers are still not convinced of investing in the much higher initial cost for a storage system. For some, the technology for thermal storages has still not been proven [2].

One of the most cost effective methods in realizing the benefits of thermal storage with use in a solar electric generating system is computer simulation. With today's technology and more powerful computers, simulations are able to closely match real operating systems in performance and running operations in a reasonable amount of time. Using a computer allows a researcher or developer the freedom to change operating parameters as well as plant configurations for optimizing with little cost compared to an actual system. Most projects involving a solar electric generating system or a storage system use some form of computer simulation. Currently there are several programs that exist to aid in the design, analysis and/or sizing of power generating plants as well as the design for thermal storage. This should be the first step in developing a large-scale SEGS with thermal storage.

Literature Review

Many researchers using computer programs have developed techniques and methods to better realize the benefits provided by thermal storage. One successful study includes work performed under an NREL contract involving Nexant, Kearney & Associates and Duke Solar Energy, LLC in the development of a concept for a two-tank indirect thermal storage system. This 6-12-hour storage system was designed for use with a 50 MWe (net) parabolic trough plant.
using a molten-salt fluid as the storage medium and an oil heat transfer fluid within the solar field. Transfer of energy between the solar field and the storage takes place using an oil-to-salt heat exchanger. Computer simulations were performed using the GateCycle program to model the steam Rankine cycle and an in-house program developed in Excel (Excelergy) to model the two-tank storage system. The project was able to show a combined, detailed plant and storage analysis to realize the impact of costs, efficiencies and revenues [3].

From the work that was performed and the promising results, the concept for this two-tank storage system is now being implemented in the AndaSol trough plant under development in Spain [3].

In another two-tank thermal storage project, a 3-hour storage system was implemented at Solar Two. This solar electric generating system used a central receiver surrounded by a field of heliostats and operated during the late 90’s [4]. The 107 MWh storage system used a molten-salt as the storage medium and as the heat transfer fluid (HTF) within the central receiver. This eliminated the need for a heat exchanger between the field and storage system, which increased efficiency with a lower cost. Plant data was collected and compared with computer simulation data using the program SOLERGY. The testing and evaluation was declared successful in quantifying the performance of the system for future projects [4].

In a study performed by Sandia, a storage tank was developed for use with a parabolic trough power plant using a single tank thermocline. The 2.3 MWh thermocline contained a solid media to store most of the thermal energy and a
molten-salt was used as storage fluid. The benefit of using a thermocline system is that initial costs are not as high as the costs associated with a two-tank system [5]. However because it is a single tank system, a non-uniform temperature profile emerges towards the ending of the discharging cycle.

The study was able to show though, that use of a thermocline system could maintain sufficient stratification while reducing initial costs compared to a two-tank system [5].

In a combined effort between the Solar Energy Laboratory (SEL), Sandia Laboratories and the German Aerospace Centre (DLR), a computer model of the 30 MWe SEGS VI plant at Kramer Junction in California was developed using the simulation software TRNSYS [6]. Only the solar side of the plant was modeled but it had less than a 10% deviation between the model and actual plant data [6].

Scope of Project

This project was developed to further assist the solar community in the design and realization of the benefits of a storage system with a solar electric generating system. It has been shown that to correctly model a thermal storage system for use in a SEGS plant, both have to be modeled together as one entity [1], [3], [7]. The program TRNSYS with IISiBat has been selected as a simulation tool for this project because of its ease of use in the creation and design modifications of transient systems. TRNSYS with IISiBat also allows users to create custom parts within the system such as different storage models or system configurations.
Two new component types were developed for use within TRNSYS that models three different types of sensible thermal storages. These two components were then analyzed with a solar electric generating system simulation model; the SEGS VI model that was previously developed by the Solar Energy Laboratory, Sandia Laboratories and the German Aerospace Centre (DLR).

One component contains a fully mixed tank model, stratified tank model and a plug flow tank model. The component has been developed such that the inputs and parameter specifications are similar so that all three models could be easily placed into one component type. A single, cylindrical direct storage tank with one inlet and one outlet that evaluates fluid properties as a function of temperature is representative for all three models.

The second component is a storage controller that passes along pertinent charging, dwell or discharging information to the storage and integrates the storage into a SEGS model.

The results obtained from this project show different extended power generation characteristics for each model. It is the interest of this project to demonstrate that by using different types of storage models with a given SEGS (SEGS VI), the results for power generation may yield a better storage tank model over the other tank models. These two new components could also be utilized with other specific SEGS plants to provide researchers, developers and/or investors with information about how to design a thermal storage system integrated into a specific SEGS plant. Depending upon the objectives for the
thermal storage (i.e. longer duration for extended power generation or a high amplitude), a more informed decision could be made for selecting a type of storage based upon results from an integrated simulation with different storage models.

Results are provided for each storage tank integrated into the SEGS VI simulation model for temperature distribution and power generation.

TRNSYS

TRNSYS (TRaNSient sYstems Simulation program) is an equation solver that simulates transient systems that a user can create using a modular approach. Developed by the University of Wisconsin, Madison's Solar Energy Laboratory, it was originally designed for simulating the transient solar behavior for solar hot water heating systems. It now also encompasses simulations for solar thermal systems, wind systems, fuel cells, HVAC and PV systems [8]. The modular approach within TRNSYS allows a user to create their own system in an environment either using a programming code (FORTRAN, C) or within a windows environment using a supplemental program, IISiBat (Intelligent Interface for the Simulation of Buildings). It also provides the user with a large range of freedom for systems design as well as for easy design modifications in between simulations.

A user creates a system by selecting different components (condenser, pump or solar panel) within TRNSYS and specifies the connections between the components. Each component can represent a physical component of the
system like a pump or turbine stage or it can represent an intangible component like a steam property calculator or data reader module. Components are actually subroutines that are usually written in FORTRAN (although it is possible to write them in C). All the components are compiled and linked within a dynamic link library (.dll) in which the TRNSYS program accesses during a simulation by reading an input file also known as a deck file. A deck file can be directly created using a text editor like Notepad or it can be generated by IISiBat using a Windows interface. Unless the user is quite familiar with creating TRNSYS deck files and a programming language, it is much easier to use IISiBat to generate deck files. Figure 1.1 shows what the IISiBat window looks like with a few components linked together to form a simple system.

Figure 1.1 IISiBat Windows Interface with Global Infos Window
To generate a deck file using IISiBat, users first create their own system using either default components or by creating new ones and linking the components together. Once the system is described and connected together, the user then specifies simulation information through another window, Global Infos for start, stop times, time step, convergence tolerance and other parameters. This can also be seen in Figure 1.1. The deck file is then generated with a click of the mouse. An example of a deck file for the corresponding system in Figure 1.1 can be found in Appendix F.

Once the deck file is completed, a simulation can be started with another click of the mouse. TRNSYS reads the deck file and calls each component in the order specified (component order can be specified in the Global Infos window using the Component Order tab). For more complex systems such as the SEGS VI model, many components have recyclic informational loops. This means that some components are called before another component is called in which the latter sends an input to the prior component. This is shown in diagram form in Figure 1.2.

![Diagram of a Recyclic Information Loop](Image)
As TRNSYS calls components, it recognizes if a recyclic loop exists and ‘tags’ these components to call again after it goes through the complete list of components. TRNSYS also performs convergence checking between the inputs (which is actually the output of another component) of each component during each iterative call. Iteration continues until a user specified tolerance or a maximum number of iterations are met.

TRNSYS comes with a default component library (trnlib.dll) that allows any user to start creating simulations. Depending upon the specific area that is to be studied, there are other libraries available to users who have signed a User’s Agreement. Some of these libraries include solar thermal electric components (STEC) and hydrogen energy systems (HYDROGEMS). Other individual components can also be downloaded free of charge from the TRNSYS website. More information about the STEC library can be found in Appendix A.

TRNSYS is currently being used worldwide and has a large network of component developers. Components are encouraged to be shared and have to be shared if a user wants access to other developed components. This aids the solar community in advancement by using a network that spans that globe.

**Thermal Storages in TRNSYS**

Currently there are two different types of sensible thermal storage components that may be used within a SEGS simulation and are contained
within TRNSYS' default library. These include a stratified and plug flow component (Type 4 and Type 38)\(^1\).

Type 4 or the stratified fluid storage tank is modeled by using an N (N<16) number of fully mixed segments of volume. A user may specify variable node sizes, inlet locations to be either fixed or variable, up to two-auxiliary heaters, loss coefficients for each node and losses to a gas exhaust flue. The model also incorporates the effects due to boiling within the tank if it should occur [9].

The Type 38 or the plug model has variable sized segments of fluid that are governed by the simulation time step, flow rates, heat losses and auxiliary input. Inlet positions can be specified as either variable or fixed. Much of this model is similar to the model within the SOLERGY program with the added benefits of being able to specify an auxiliary heater, conduction between segments, horizontal or a vertical cylindrical tank and different thickness insulation values [9].

Other work has been done on both models to enhance their capabilities [10], [7]. One author made a recommendation that future research should encompass the development of an easy method to quickly enable a user to switch back and forth between the stratified and plug flow model within TRNSYS [10]. Currently the way each model exists in TRNSYS, each requires different set up procedures (i.e. required inputs and parameters), which makes switching between the two different models cumbersome and time-consuming.

\(^1\) Type X (where X is a number) is how TRNSYS keeps track of each component.
An issue in using the Type 4 stratified tank model is that when a large number of nodes are used with a high flow rate, the model could become unstable because of too big of a time step. The flow rates that are seen in a large-scale SEGS plant are extremely high compared to a hot water heating system, which may create instability in the model.

One of the new components that was developed during this project was designed to easily combine three different model types into one without interference of differing parameter, inputs or outputs. Also, an internal time step was incorporated within the stratified model to prevent instability problems.

SEGS VI

The actual SEGS VI is a 30MWe net parabolic trough located at Kramer Junction, California and has been in operation since 1988. It is a hybrid system of solar and natural gas that utilizes a single reheat with a steam turbine system. The plant approximately has 188,000 square meters of reflective aperture area using 800 LS-2 SCA's. An aerial view of the plants at Kramer Junction is shown in Figure 1.3.
Therminol VP-1, a synthetic oil is used as the heat transfer fluid (HTF) that circulates through the troughs and to the steam train (preheater, evaporator and superheater). The flow is varied to maintain an output temperature from the field of approximately 391°C. Exiting steam conditions from the superheater to the high-pressure turbine are about 100 bar at 371°C. The plant is allowed to operate up to a maximum of 25% natural gas. A schematic of the plant is shown in Figure 1.4.
As mentioned previously, a simulation model was developed from the efforts of the Solar Energy Laboratory, Sandia Laboratories and the German Aerospace Centre (DLR) using TRNSYS. The developed model was verified by comparing simulation data with actual plant data for a high solar radiation day and a cloudy day [6]. Figure 1.5, Figure 1.6 and Figure 1.7 show the simulation model within IISiBat.
Figure 1.5  SEGS VI Simulation Model in IISiBatt

Figure 1.6  Solar Side of SEGS VI in IISiBatt

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While there was good agreement between the model predictions and the actual plant data with usually errors less than 10%, there was still room for improvement of the turbine control logic and adding of thermal capacitance to the model [6]. The project did successfully demonstrate the capability of using TRNSYS for a detailed analysis and for the possibility of evaluating proposed trough storage systems.
CHAPTER 2

DEVELOPMENT OF COMPONENTS

To help aid in establishing the benefits of using a sensible thermal storage system with a SEGS in a quick and easy manner, two new components were created using IISiBat and the Compaq Visual Fortran program for use with TRNSYS. One component, the Sensible Storage Modeler was designed with three different types of sensible storage models to represent a large range of modeling techniques. The second component, the Storage Controller was designed to relay to the storage model a storage mode of either charging, discharging or a dwell cycle and other associated information. The Storage Controller also integrates the Sensible Storage Modeler component into a larger simulation, like a solar electric generating system simulation by allowing the storage and other nearby components to 'talk' to each other. These two new components used together allow for easy changing between storage models for any level of user for either research and/or development purposes and can be used with any SEGS simulation.

Sensible Storage Model Component

Many models have been developed for predicting the temperatures within a storage tank. Only one-dimensional models were selected for this project.
because of the reduced computational time required compared to a two or three-dimensional model [11]. Moreover, the actual design of any single storage tank would try to inhibit any form of mixing by use of advanced diffusers to keep a high degree of stratification. A second and/or third dimension would enhance mixing effects and degrade stratification [11].

The first of three models to be selected was a fully mixed storage tank to represent the most basic type of modeling of thermal storage. It assumes all incoming flow creates a fully mixed condition within the tank such that no thermal stratification can be formed. Due to a fully mixed condition, conduction does not play a part in energy transfer within this model. While this type of model is straightforward in implementing into a programming code and may be of some use to users, it usually does not yield as detailed results compared to the other two models. This is usually the worse case scenario for thermal storage since this type of model tends to overestimate the energy required to charge it due.

The second model, a stratified tank allows for stratification to occur using two mechanisms: 1) mixing of mass flow between segments of different temperatures; and 2) vertical conduction. It is the closest model that approximates most real storages but it is also more complex in implementing into a programming code and requires extra care when using high flow rates. Too high of a flow rate may cause mass overflow within a node which may cause the model to become unstable. This model represents the different degrees of stratification between the fully mixed model and the third model of storage – plug flow.
A plug flow storage tank was selected to represent the opposite end of the spectrum from a fully mixed tank for thermal storage modeling. It is an idealized case in which it is highly stratified throughout the tank. Flow enters the tank such that mixing of different temperature segments do not occur. By not allowing segments to mix with each other, the segments move either up or down depending upon the storage cycle like in ‘solid chunks’. This creates a maximum degree of stratification within the tank. Implementation of a plug flow model in a simulation does require slightly more effort than the fully mixed model but not nearly as much as a stratified model. It can provide the best scenario results for use with a solar electric generating system. This modeling technique is very beneficial for researchers and developers who have the capability of building a system with equipment that produces a near non-mixing environment inside a storage tank such as two-tank storage system.

Each model was developed with a simple approach to allow for user friendliness in comparing modeling techniques within a given SEGS. This also allows for a shorter computer computation effort compared to individually simulating all three different storage models while still being able to produce insight to the overall system for the user. Some simplifications and assumptions that were made include the following: a single direct storage cylindrical tank, no ambient losses, no external heaters, one inlet and one outlet for flow, one-dimensional vertical conduction and no convection effects. While there are four primary mechanisms that contribute to the degradation of energy within a storage tank: (a) heat losses to the ambient; (b) conduction from the hot to cold layers;
(c) vertical conduction within the tank walls which causes natural convection; and
(d) mixing introduced to incoming flows, factor (d) is generally the major cause of
destratification and so was also included [7], [11].

Fluid properties were modeled as functions of temperature. Many simulation
models do not contain variable properties, including the standard storage models
in TRNSYS. However, depending upon the range of temperatures to be used,
fluid properties could fluctuate significantly. The correlations for specific heat and
density verses temperature were obtained for Therminol VP-1 from correlations
included in the SEGS VI model while the thermal conductivity was obtained from
a fluid property program, Monsanto and are given in Equation (1a), (1b) and (1c),
respectively.

$$C_p(T) = 1.500044 + 0.00276912 \cdot T - 1.3 \cdot 10^{-7} \cdot T^2$$  \hspace{1cm} (1a)

$$\rho(T) = 1067.342 - 0.588701 \cdot T - 0.00088586 \cdot T^2$$  \hspace{1cm} (1b)

$$k(T) = 9 \cdot 10^{-12} \cdot T^3 - 2 \cdot 10^{-7} \cdot T^2 + 2 \cdot 10^{-5} - T + 0.1475$$  \hspace{1cm} (1c)

The specific heat is in units of kJ/kg*K with the temperature given in Celsius.
Density is in units of kg/m^3 with the temperature also in Celsius and the thermal
conductivity is in units of W/m*K with temperature in units of Kelvin.

All three tank models were derived using the conservation of energy on a rate
basis by writing an energy balance for the tank (fully mixed model), each node
(stratified model) and for each segment (plug flow model). The general form of the conservation of energy is given in Equation (2).

\[ \Delta E = E_{in} - E_{out} \]  

(2)

To keep the models simple, transports of energy that could enter or leave the control volumes included the mixing of mass within the tank and conduction in the vertical dimension. Convection of any type as well as ambient losses were not included due to the many varying circumstances that could influence these effects as well as also trying to maintain a straightforward approach for the models.

Once the governing equations were written for each model, the equations were discretized using a finite difference method to allow computer entry to solve for the new temperatures at the next time.

**Fully Mixed Model**

The energy balance for the fully mixed model is the rate of change of energy within the tank equal to the difference between the energy in due to the incoming mass flow rate and the energy out due to the outgoing mass flow rate. This is shown in Equation (3). Because the tank is assumed to be fully mixed at all times, there is no conduction within the tank.

\[ M_{tank} \cdot C_{p \text{ tank}} \cdot \frac{dT}{dt} = M \cdot C_{p \text{ in}} \cdot (T_{in} - T_{tank}) \]  

(3)
The energy balance can be rearranged solving for the new temperature in terms of its old temperature. This model uses an explicit finite method to determine future temperatures and is shown in its discretized form in Equation (4).

\[
T_{\text{now}} = T_{\text{tan} \, k}^* + \frac{M \cdot C_{p_{\text{in}}}}{M_{\text{tan} \, k} \cdot C_{p_{\text{tan} \, k}}} \cdot (T_{\text{in}} - T_{\text{tan} \, k}^*) \cdot \Delta t
\]  

(4)

A schematic of the fully mixed model is shown in Figure 2.1.

---

**Stratified**

The stratified tank is modeled by 'breaking' the tank into 'N' number of parts called nodes. Each node can be classified as either a top, interior or bottom node.
For each type of node, the energy equation takes on a different form. This model uses the mixing of mass within nodes and one-dimensional vertical conduction for energy transports. The energy equation for all three types of nodes can be written as the time rate of change of the node equal to the energy difference of the mass entering and leaving the node plus the energy difference of conduction to and from the node. These are shown in Equations (5a), (5b) and (5c) for the top, interior and bottom nodes, respectively.
These energy equations can be discretized so that the new temperatures can be determined. The stratified model employs an implicit finite difference method that solves for future temperatures of all nodes in terms of the future temperatures of the nodes adjacent to it. The result of the energy balance for each node is a system of equations that need to be simultaneously solved.

The benefit of using an implicit method for the solution to many equations is that it eliminates the need for a stability check that is necessary when using an explicit method. The programming for an implicit method of solution over an explicit method is slightly more complex, but there are many coded subroutines readily available that can be obtained to solve a system of equations. A Gauss-Seidel method was selected for solver of choice so besides discretizing the energy equation, coefficients had to be found for the temperature variables in terms of charging and discharging. This resulted in six different equations and is
shown below. Equations (6a), (6b) and (6c) are for charging and Equations (7a),
(7b) and (7c) are for discharging.

\[
\frac{-M_{\text{top}} \cdot C_{\text{p, top}}}{\Delta t} + \frac{k_{\text{top}} \cdot A_{e}}{\Delta x} \cdot \frac{T_{\text{top}}}{\Delta x} = M_{\text{in}} \cdot C_{\text{p, in}} \cdot T_{\text{in}} + \frac{k_{\text{top}} \cdot A_{e}}{\Delta x} \cdot T_{\text{top}+1} + (6a)
\]

\[
\frac{M_{\text{top}} \cdot C_{\text{p, top}}}{\Delta t} \cdot T_{\text{top}}^{i-1} + M_{\text{in}} \cdot C_{\text{p, in}} \cdot T_{\text{in}} = 0
\]

\[
\frac{-M_{i} \cdot C_{p_{i}}}{\Delta t} - M_{\text{in}} \cdot C_{\text{p, in}} \cdot \frac{A_{e}}{\Delta x} \cdot \left( k_{i} + k_{i-1} \right) \cdot T_{i} + \frac{k_{i} \cdot A_{e}}{\Delta x} \cdot T_{i+1} + (6b)
\]

\[
\left( M_{\text{in}} \cdot C_{\text{p, in-1}} + \frac{k_{i-1} \cdot A_{e}}{\Delta x} \right) \cdot T_{i-1} + \frac{M_{i} \cdot C_{p_{i}}}{\Delta t} \cdot T_{i-1} = 0
\]

\[
\frac{-M_{\text{bot}} \cdot C_{\text{p, bot}}}{\Delta t} - M_{\text{in}} \cdot C_{\text{p, bot}} - \frac{k_{\text{bot-1}} \cdot A_{e}}{\Delta x} \cdot T_{\text{bot}} + (M_{\text{in}} \cdot C_{\text{p, bot-1}} + (6c)
\]

\[
\frac{k_{\text{bot-1}} \cdot A_{e}}{\Delta x} \cdot T_{\text{bot-1}} + \frac{M_{\text{bot}} \cdot C_{\text{p, bot}}}{\Delta t} \cdot T_{\text{bot}}^{i-1} = 0
\]
A user specifies a diameter and a height for the dimensions of the tank as well as how many nodes (N) are to be modeled and an internal time step. The more nodes that are specified in the model provide a better degree of stratification, although it does take more computation time. An internal time step allows for calculation of the temperature of the nodes when the flow rate during the overall simulation time step would otherwise exceed the mass in the nodes within the tank. This would result in erroneous data. A balance between the number of user specified nodes and internal time step can create a detailed analysis without using too much computational time. The program has been designed in the event the mass flow rate within an internal time step does exceed
the mass in any node, an error message is generated within the list file. (A list file is a file generated during execution of a TRNSYS simulation and errors may be printed to it).

**Plug Flow**

The plug flow storage is modeled as a number of variable volume segments within the tank. The number of segments as well as the volume of each segment are a function of the simulation time step and flow rate. When fluid enters the tank, either from the top or bottom (charging and discharging, respectively), a new segment is formed while at the opposite end of the tank, the same amount of mass is subtracted from the storage. This results in the reduction in volume of at least one segment and sometimes the elimination of one or more segments. If more than one segment exists within the tank and the segments are of different temperatures, one-dimensional vertical conduction is allowed to take place. Figure 2.3 illustrates this process.
Figure 2.3  Diagram of Plug Flow Tank Model
The energy balance for each segment is simply the change of energy of the segment equal to the difference between conduction entering and leaving the segment. The top and bottom nodes have only one term for conduction while an interior node has two terms and can be seen in Equations (8a), (8b) and (8c).

\[
M_{\text{top}} \cdot C_{p_{\text{top}}} \cdot \frac{dT}{dt} = k_{\text{top}} \cdot A_c \cdot \frac{dT}{dx} \]  \hspace{1cm} (8a)

\[
M_{i} \cdot C_{p_{i}} \cdot \frac{dT}{dt} = k_{i-1} \cdot A_c \cdot \frac{dT}{dx} - k_{i+1} \cdot A_c \cdot \frac{dT}{dx} \]  \hspace{1cm} (8b)

\[
M_{\text{bot}} \cdot C_{p_{\text{bot}}} \cdot \frac{dT}{dt} = k_{\text{bot}} \cdot A_c \cdot \frac{dT}{dx} \]  \hspace{1cm} (8c)

To solve for the new temperature of the segments, the energy equations were solved for the time derivative and the conduction terms were discretized and are shown in Equations (9a), (9b) and (9c).
TRNSYS has a built in equation solver (DIFFEQ) for linear ordinary
differential equations in the form of Equations (9) and was utilized for solving the
new temperatures of each segment.

Since the segments within the tank do not mix mass between one another, an
internal time step was not needed as it was for the stratified tank model. This
makes the computation for this model almost as quick as the fully mixed model.

The FORTRAN code and the parameters and inputs using IISiBat are given in
Appendix F and B, respectively.

Storage Controller

The Storage Controller component works with the Sensible Storage Modeler.
It passes information such as storage cycle (charging, dwell or discharging), flow
rate and temperature associated with the type of cycle. It also integrates the
storage into the system. The Storage Controller used for this project was
designed to work with the TRNSYS SEGS VI simulation model, although it could
be used with other SEGS models. In any case, some form of a storage controller is needed when using the Sensible Storage Modeler component.

The control logic for charging the storage is performed by monitoring the power generation of the power plant. If the plant is producing power over a user specified minimum power generation and the storage tank is not completely charged, it will divert some of the HTF coming from the solar field to the storage. The amount of diverted flow is a function of a user specified minimum power generation and the actual plant power generation. This is shown in Equation 10.

\[
M_{\text{charge}} = M_{\text{through}} \cdot (1 - \frac{P_{\text{act}}}{P_{\text{ref}}})
\]  

(10)

At the same time fluid is entering the tank during a charge cycle, cold fluid from the bottom of the tank is exiting and returns back to the solar field.

The basis for specifying a minimum power generation is so that the plant can operate at least at some level of power output while charging the storage. It was noticed that during the early stages of charging, the power generation out of the plant hovered around the specified minimum power as expected. But as the solar intensity increased as the day progressed, the flow rate within the solar field significantly also increased so that a linear function no longer appropriately diverted enough HTF to the storage to maintain a power generation near the specified minimum power. While the linear function logic worked for generating results, using another curve fit that operates along more of an exponential trend may prove better.
Charging begins when the power generated is higher than the user specified minimum and the temperature from the trough is at least higher than 5°C of the temperature at the top of the tank. Once charging starts, it continues until the power generated is less than the user specified minimum or the temperature at the bottom of the tank is within 5°C of the incoming fluid. This bottom check prevents wasted energy passing through the storage when it is fully charged.

Control logic for the discharging cycle monitors the steam pressure out of the superheater instead of the plant’s power generation. Originally the discharging control logic did use power generation as a signal to discharge but it was found that the discharging of the storage was occurring too late to prevent the turbines from shutting down during the simulation. The results showed that the discharging of the tank would restart the turbines through its warm-up and synchronization periods only to shut down again and a large gap was observed for results of the power generation curve between turbine shut down and the power generated by storage. It was also observed that a lot of run-time errors developed when using a feedback control system. To avoid these problems, discharging was kept at a constant flow rate instead of using a feedback system like the charging logic.

The FORTRAN code and the parameters and inputs using IISiBat for this component are also given in the Appendix F and B, respectively.
CHAPTER 3

PROCEDURES

The solar side of the SEGS VI model is set up so that the trough model controls the HTF flow rate. The trough model was set originally to maintain a fluid (Therminol-VP1) temperature of 350°C by varying the flow rate. From the trough the HTF goes to an expansion tank that also acts as thermal capacitance for the trough model. (When the SEGS VI was obtained, work was being done on refining the trough model. It was found that the trough model did not appropriately model capacitance just before sunrise and just after sunset. Several attempts were made to correct for this which yielded convergence problems [12]). Fluid flow then continues to a splitter in which determines if the HTF is hot enough to be sent to the steam train. If the fluid is 260°C or higher then flow continues, otherwise the flow is diverted back to the trough in which this is called the solar recirculation loop.

When the HTF is allowed to bypass the solar recirculation loop, 87.5% is then sent to the steam train and the remaining 12.5% is sent to the reheater by way of another splitter. Once the separate flows have gone through the reheater and the steam train, the streams are recombined and reintroduced into the solar recirculation loop to return to the trough. Figure 1.6 shows the solar side of the SEGS VI model in IISiBat.
Storage Implementation

The two new components were combined in IISiBat to form a macro. A macro allows two or more components to be combined to visually make one icon appear on the screen. This presents the simulation window in a cleaner appearance. The new storage macro was inserted in the SEGS VI model outside of the solar recirculation loop and after the splitter to the steam train and reheater on the steam train side.

All inputs to the storage macro go to the Storage Controller component. Besides the flow from the trough, this also includes HTF returning from the steam train, net power generation of the plant and steam pressure out of the superheater.

Outputs from the storage macro that are from the Storage Controller includes flow to the steam train and flow returning to the trough. A partial viewing of how the storage macro appears in the SEGS VI model is shown in Figure 3.1. A full viewing can be found in Appendix D.
Inside the storage macro, information between the Storage Controller and the Sensible Storage Modeler is exchanged. The Storage Controller sends a signal, 1, 2 or 3 which indicates charging, dwell or a discharging mode, respectively. Along with a storage mode, information about flow rate and temperature are also relayed. In return, the Sensible Storage Modeler sends the temperature at the
top and bottom\(^2\) of the tank. A viewing within the storage macro that shows the interconnection between the Storage Controller and the Sensible Storage Modeler is shown in Figure 3.2.

![Figure 3.2 Storage Controller and Storage Modeler Interconnections](image)

Beginning of a simulation starts at 12:00 a.m. so it is assumed the storage is fully discharged and is at a uniform temperature of 250°C. As the simulation progresses and the solar radiation increases, the Storage Controller monitors the

\(^2\) When referring to the temperatures of the top and bottom of a tank, it is understood that for the fully mixed tank this is the average temperature.
net power generation and the temperature at the top of the tank. When the plant starts generating more power than the user specified minimum power and the temperature at the top of the tank is at least 5°C lower than the temperature of the fluid coming from the trough, some flow is diverted to the storage for charging. Equation (10) shows how much flow is diverted.

Charging continues until either the plant's power generation falls below the user specified minimum power or the temperature at the bottom of the tank is within 5°C of the incoming fluid (fully charged state). A user minimum power specification of 8 MW was used for running simulations during this project. Using a higher minimum power usually resulted in more run-time errors or less charging of the storage and less extended power generation.

Discharging of the storage occurs when the steam pressure from the superheater to the turbine falls below a user specified minimum steam pressure and if the temperature at the top of the tank is higher than 300°C. Discharging continues until the top of the tank drops below 300°C. The SEGS VI model is set to shut down the turbines if the steam pressure drops below 16.2 bar so the user specified minimum was set at 25 bar. Any user specified minimum steam pressure less than 25 bar almost always resulted in the turbine shutting down before the discharging of storage could prevent it.

\[ \text{Equation (10)} \]

\[^{3}\text{From earlier simulations it was found that discharging storage at a temperature less than 300°C caused the turbines to shut down so there was no point in continuing discharging at temperatures less than this.}\]
If none of the conditions are met for either charging or discharging, the storage goes into dwell mode where no flow is sent to or from the storage. It is completely bypassed using the Storage Controller.

Initial Trial Simulations

Once the Storage Controller and the Sensible Storage Modeler were linked into the SEGS VI model, a 13m x 18m storage tank was used initially for trial runs. Throughout the project, many complications arose in which indicated that a more refined SEGS VI model was needed for running thermal storage simulations. It was also observed that recyclical components within some simulations might not have been all recalled. A listing of problems encountered throughout the project is summarized in Appendix C.

At least two components, the trough and turbine control component within the SEGS VI model were not the most current components. An effort was made to obtain the current models with little success. Several simulations also resulted in non-convergence of the trough model and temperature spikes above the set temperature for the trough. Another indication of an early version was that in simulating the SEG VI model without any storage (no changes) for a year resulted in several FORTRAN math run-time errors. A summary of these run-time errors can also be found in Appendix C.
Simulation Parameters

After some time of 'feeling out' the range of parameters that could be changed regarding the implemented storage components without too many problems (i.e. run-time errors, simulation convergence problems or component convergence problems) arising, the following was selected for running simulations. Seven days during the summer were used from July 13 through July 19 (day 195-201, hour 4656-4824). These days contained high solar radiation in which no run-time errors were detected and the trough model did not contain any high temperature spikes.

Three discharging flow rates were selected of 400,000 kg/hr, 500,000 kg/hr and 600,000 kg/hr. These flow rates are very low compared to what the flows are normally when the trough model is operating during the middle of a hot summer day. However, when a high discharging flow rate was used (higher than 800,000 kg/hr), run-time errors were almost constant or the discharging of the storage would have no effect upon the extended power generation. Also, good extended power generation was observed within this range of discharging flow.

Two different sizes of storages were selected based upon the thermal energy needed to run the plant for an extended 1 and 2 hours. Sizing of the tanks based upon these criteria was first performed by determining what the steam train's duty cycle was throughout a day relative to the plant's power generation. The steam train duty was determined by using the change in enthalpy of the HTF through the steam train multiplied by the HTF flow rate to obtain units in MW. The steam train duty was then paired with the corresponding power generation.
for that current time step. A total of nine days from July 12 to July 20 was used and the data was plotted as can be seen in Figure 3.3.

![Steam Train Duty vs. Net Power Generation July 12 - 20](image)

**Figure 3.3 Steam Train Duty vs. Net Power Generation for SEGS VI**

The data points that appear towards the top right that do not tend to follow the linear positive slope are during start-up of the plant when the fluid is not warmed up yet and the plant is still cold. As the plant warms up which is a matter of about 1½ to 2 hours, the data points start to follow the linear trendline. As the day progresses and the turbines start to shut down, the steam duty continues to
follow a linear trend due to the capacitance of the system rather than following the initial high duty cycle required in the morning.

The SEGS VI plant is rated at 30 MWe net power production, but the results from the nine test days did not peak 30 MWe. A power generation for determining the required steam train duty for sizing the storage was selected at 25 MWe. The corresponding steam train duty is approximately 67 MWt.

For a 1 and 2 hour period, the required energy for a 67 MWh and a 134 MWh storage tank is 241.2 MJ and 482.4 MJ, respectively. Using the specific heat and density of Therminol-VP1 at a maximum temperature of 350°C, a required volume of fluid can be determined and the dimensions. A 16.5m diameter with a height of 12.3m was used for the 1-hour storage tank and a 20.3m diameter with a height of 16.2m was used for the 2-hour storage tank.

Two solar field sizes were also used for simulation study. The SEGS VI model has a standard solar field size of 188,000 square meters of reflective aperture area, which was used for the first size. The second field size was an increase of the original size by 20%. Any larger of a field caused flow rates to exceed the maximum capacity of the solar field pump and temperatures to exceed 450°C, which is over the safe operating limits of Therminol-VP1.

The SEGS VI model was originally received with a simulation time step of 1 hour. However with the HTF flow rates ranging from 144,000 kg/hr to over 1,000,000 kg/hr, the flow rate could exceed the total mass within the entire storage tank. A time step of 0.5 hours was selected to prevent storage wash out and it also produced the least amount of run-time errors.
Simulation Runs

A total of 36 simulations were run for generating results using the parameters discussed in the previous section. From these simulations, graphs were generated for each model for temperature distribution versus time, average temperature versus field size and power generation versus field size. For comparison of the different storage models, graphs were generated for average temperature versus time and power generation versus time. Comparisons were also made for power generation using storage and without storage.
CHAPTER 4

RESULTS

Two reoccurring trends found within the power generation graphs for all tank models should be pointed out. First, the original intent for sizing the tanks was to store enough energy in the tank so that the plant could operate 1 or 2 hours more while generating approximately 25 MWe. Initial simulations indicated that the discharging flow rate had to be hard-coded within a limited range (as discussed in the Storage Controller section and the Simulation Parameters section) which, was much less than normal operating flow rates. Normal flow rates that serviced the steam train and reheater from the trough were greater than 1,000,000 kg/hr. This was about more than double than what the flow rate was when discharging of the storage occurred. So typically the extended power generation using storage resulted in less than 25 MWe with longer time durations than designed.

The second trend was that in many instances a 'gap' developed between the end of the plant running directly from the trough and the beginning of a storage discharging cycle. As mentioned in the Storage Controller section, this gap was due to premature turbine shut down before the effects of the discharging storage could maintain a continuous power generation. Three factors have been identified as possible causes for this unwanted effect.
In many instances, premature turbine shut down was observed when the power generated just before discharging occurred was much higher than the power being generated by the charging and discharging periods. This appears as a spike in the middle of the power generation graphs. The spiking was caused by the end of the charging cycle and the beginning of a dwell cycle. When a dwell cycle starts, HTF flow is no longer being diverted to storage and so the full flow from the trough then goes to the steam train and reheater. This creates more superheated steam and a jump in power production.

It is during the dwell cycle that the plant is operating at a high level of generation in which flow rates and temperature are very high. However when conditions change so that the storage starts discharging, a much slower flow rate is seen than what it was at the previous time step. The momentum of the plant's previous state causes the power to drop well below the power generation from the discharging fluid. In other words, the discharging of storage is not enough to 'catch' the drop in operating conditions to the level of extended power generation and so a 'gap' appears in the power generation graph.

The second factor may have been the calling order of components that TRNSYS uses. The SEGS VI model is an extremely complex system within TRNSYS and during initial simulations, results seemed to indicate that not all components were being recalled as expected. Two observations were made that could be from this occurring: 1) when a pump was placed into the simulation to control the discharging flow rate based upon a demand flow rate from the Storage Controller, discharging sometimes never occurred depending upon what
the calling order of the pump and Storage Controller was and; 2) 'gaps' in the power generation curve as discussed above also sometimes occurred when a high power generation spike did not previously occur. The storage discharges when the steam pressure is below a user input which is well above the turbine shut down value. If recyclic components are properly being called, one would expect not to observe premature turbine shut down under these conditions.

The third possible factor for premature turbine shut down could be due to the Turbine Controller. The Turbine Controller component makes the decision of how much steam goes to the turbine and how much is diverted due to a minimum quality of steam not being met. It was later determined that the Turbine Controller that was present in the SEGS VI model was not a current model and used a different control strategy than monitoring the steam pressure from the superheater [14].

Graphical Results

Graphs in this section are shown first by model type for the 500,000 kg/hr discharging flow rate for each size tank using two solar field sizes for power generation and average temperatures. The other remaining graphs generated using the two other flow rates of 400,000 kg/hr and 600,000 kg/hr are included in Appendix E. Results using a discharging flow rate of 500,000 kg/hr generally produced results that had less run-time errors and non-convergence problems. Graphs are then presented for comparisons between the models for power generation and average tank temperatures for both size tanks.
Power generation without storage for the 7 days that were studied is also included in Appendix D for reference. Temperature distributions for the stratified and plug flow model are also given in Appendix E for each tank size and flow rate.

**Mixed Tank Model**

Figure 4.1 shows the power generated using the 1-hour tank with a discharging flow rate of 500,000 kg/hr for the two different solar field sizes. Each 'hill' shown in the graph is representative for 1 day.

![12x16/500 Mixed Power Generation vs. Field Size](image)

**Figure 4.1** Fully Mixed Power Generation 1-hour tank (500)
Notice that premature turbine shut down can be seen between the normal power generation and the power generated by storage. The power generation maximum using storage is not as high as originally designed, but it is as expected due to the slower discharging flow rate. The power generation is also longer than the designed 1 hour because of the slower flow rate.

Using a flow rate of 500,000 kg/hr did produce several days that did not experience premature turbine shut down however, using the larger field size almost always produced premature turbine shut down. This may have been caused in part by the large power generation spike seen just before discharging occurs. Spiking in the power generation curve is caused when the storage changes from a charging cycle to a dwell cycle. The larger field just about always yielded a fully charged storage so that a dwell cycle took place and caused a spike to appear. The difference in operating conditions just before and after the discharging of the storage may have caused the gapping between the normal power generation and storage power generation.

Day 4 in the figure corresponds to the best day for continuous power generation using the standard field size. The extended power generation was for an additional 4 hours ranging from 15 to 7 MWe. Day 5 corresponds to the best day for continuous power generation using the larger field size with power generation also ranging from 15 to 7 MWe.

The sloping curve of the extended power generation directly follows the temperature degradation from the storage. The fully mixed model showed the quickest drop in power generation between all models which was to be expected.
Figure 4.2 is the corresponding average temperature for both solar field sizes. Results between the two different solar fields were as expected with the larger field yielding a higher average tank temperature than the smaller field.

The average temperature for the standard field never really comes to a plateau like the larger sized field did indicating that the storage tank never reached a fully charged state before discharging occurred. As expected, the larger field yields a higher average temperature.

Figure 4.3 shows the power generation using the 2-hour tank. The results also show that the standard size solar field yielded better continuous power generation days compared to the larger field (without gaps). Days 3 and 6
correspond to the best days for continuous power generation using the standard field size. The extended power generation for both days was for an additional 4 hours ranging from 10 to 6 MWe. Day 6 corresponds to the best day for continuous power generation using the larger field size with power generation ranging from 14 to 6 MWe over a period of an impressive 7 hours.

![Figure 4.3 Fully Mixed Power Generation 2-hour tank (500)](image)

Figure 4.3 Fully Mixed Power Generation 2-hour tank (500)

Figure 4.4 is the corresponding average temperatures for the 2-hour tank. The average temperature between the two solar field sizes was once again as expected.
Figure 4.4  Fully Mixed Average Temperature 2-hour tank (500)

Stratified Tank Model

Figure 4.5 shows the power generated for the 1-hour tank with a discharging flow rate of 500,000 kg/hr for the two different solar field sizes.
A 15% larger solar field size had to be used due to many run-time errors experienced using a 20% larger field. The standard field had a few days in which a fully charged tank was achieved (some spiking trends) while a fully charged tank was achieved using the larger solar field with the exception of day 5. Day 5 in general, corresponds to the lowest power generation day for the simulation without storage which, can be found in Appendix D. Day 1 corresponds to the best day for continuous power generation using the standard field size. The extended power generation was for an additional 4.5 hours ranging from 16 to 7 MWe. Day 5 corresponds to the best day for continuous power generation using the larger field size with power generation ranging from 16 to 7 MWe over a period of 4.5 hours.
Figure 4.6 shows the corresponding average temperature for Figure 4.5 and also shows a higher average temperature associated with the larger solar field.

![12x16/500 Stratified Average Temperature vs. Field Size](image)

Figure 4.6  Stratified Average Temperature 1-hour tank (500)

Figure 4.7 shows the larger tank in use for under the same operating conditions as above. This particular simulation had a run-time error associated with each of the solar field sizes. Part of day 6 and 7 could not be obtained for the standard size field, while day 3 could not be generated for the larger field.
Day 3 corresponds to the best day for continuous power generation using the standard field size. The extended power generation was for an additional 6 hours ranging from 12 to 7 MWe. Day 6 corresponds to the best day for continuous power generation using the larger field size with power generation ranging from 16 to 7 MWe over a period of an impressive 8 hours.

Figure 4.8 shows the corresponding average temperature for Figure 4.7. Note that none of the temperatures reached a plateau for either solar field size that indicated that a fully charged tank was not achieved.
Figure 4.8  Stratified Average Temperature 2-hour tank (500)

Plug Flow Tank Model

Figure 4.9 shows the 1-hour storage tank for the plug flow model. All the graphs generated using the plug flow model indicated that for both storage tank sizes and the three different flow rates resulted in a fully charged tank. This can be seen in the power generation graphs as a spiking trend. Also note that the extended power generation due to storage does not have a sloping trend to it like the fully mixed and stratified model. This is because the temperature in the tank is not subject to mixing of mass and so the cooler fluid remains at the bottom of the tank while all the hot fluid is shifted upwards and out of the tank. Power generation is stopped when the last hot segment is drained from the tank.

Figure 4.9 shows that day 1 corresponds to the best day for continuous power generation using the standard field size. The extended power generation was for
an additional 3 hours for 16 MWe. Day 4 corresponds to the best day for continuous power generation using the larger field size with power generation at 19 MWe over a period of 3 hours.

Figure 4.9  Plug Flow Power Generation 1-hour tank (500)

Figure 4.10 shows the corresponding average temperatures for the two size solar fields. Once again the temperatures were as expected, with the larger solar field yielding higher average temperatures.
Figure 4.10 Plug Flow Average Temperature 1-hour tank (500)

Figure 4.11 shows the power generation for the 2-hour tank. Aside from runtime errors, this particular simulation for the larger solar field generated some of the most unexpected results.

The standard solar field size produced results typical of what was produced from previous simulations. The larger solar field however, showed no evidence of storage discharge taking place for days 2 thru 6 as seen in Figure 4.11.

Day 3 corresponds to the best day for continuous power generation using the standard field size. The extended power generation was for an additional 5 hours ranging from 15 to 12 MWe. The larger solar field did not result in any days that could be considered for a good extended power generation day.
Figure 4.12 shows the corresponding average temperature for the power generation in Figure 4.11. The 5 days that show no extended power generation also correspond to the same 5 days in which the average temperature of the tank barely reached 300°C. When the temperature distribution of the tank is analyzed (see Appendix E) it becomes clear that the flow into the tank during discharging is much higher than it should be. Typical returning temperatures have been between 170-220°C. The temperature of the returning fluid into the tank during this particular simulation is actually between 285-366°C. This indicates that the energy from the HTF was not being transferred to the steam side of the plant. This may have been caused by a no flow rate condition on the steam side of the plant.
Figure 4.12  Plug Flow Average Temperature 2-hour tank (500)

Comparison of Models

The following graphs present comparisons between each model for power generation and average temperatures over the 7 days that were studied. The power generation for the case of no storage has also been plotted for comparison with the different storages. As with the graphs presented in the previous section, results are given for the two tank sizes using a discharging flow rate of 500,000 kg/hr. The other remaining graphs generated using the two other flow rates of 400,000 kg/hr and 600,000 kg/hr are included in Appendix E.
Figure 4.13 shows the power generation by the three tank models for a 1-hour tank size and for the case of no storage. Figure 4.14 shows the average temperature for each tank model.

![Figure 4.13 Power Generation Comparison for 1-hour tank (500)](image1)

![Figure 4.14 Average Temperature Comparison for 1-hour tank (500)](image2)

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Figure 4.15 shows the power generation for the three tank models for a 2-hour size tank and for the case of no storage.

Figure 4.15  Power Generation Comparison for 2-hour tank (500)

Figure 4.16  Average Temperature Comparison for 2-hour tank (500)
Figure 4.16 contains the average temperature for the tank models that correspond to the conditions in Figure 4.15.

Discussion

In comparing the power generation curves between the different models, several observations were made. The fully mixed model showed higher power generation than the stratified and plug flow model during times of storage charging. This was because the exiting flows for the plug model and the stratified model during charging were cooler compared to the fully mixed model. This flow is then returned back to the trough for reheating. Since the returning flow for the fully mixed model is higher in temperature than the flow for the two other models, the trough pump generates a faster flow rate to try to maintain the 350°C temperature out. The higher flow rate generates higher steam pressures and corresponds to a higher power generation. Also because of this higher flow rate, the average temperature of the fully mixed model rises more quickly than as one would first expect. The average temperature graphs comparing the models show that the fully mixed model was usually higher than the stratified model. The plug flow model usually had an average temperature around the same as the fully mixed model.

In examining the power generation and average temperature graphs that compare the three models, the days in which result in a higher temperature for the fully mixed over the plug model show up on the power generation graph as the plug flow model reaching a fully charged state quicker than the fully mixed
model. As the day progresses, the temperature of the trough has also increased to produce a slightly higher average temperature for the fully mixed model. The plug flow doesn't start recharging though, because of the control logic that has been defined in the Storage Controller. The fully mixed's higher average temperature was also seen when the tanks were not fully charged before discharging occurred.

These two trends were typical for all graphs generated for the three different models in comparing power generation. These can be seen in Figure 4.13, Figure 4.14, Figure 4.15 and Figure 4.16, which corresponds to the two different size tanks.

Another common trend that showed up throughout the power generation graphs was the appearance of ‘gaps’ between the normal power generation and the power generation by storage. Three factors were previously discussed at the beginning of the Chapter 4 that may have contributed to this effect.

The power generation during the discharging cycle was consistent and expected for the stratified and plug flow model to produce higher values than the fully mixed model. This was due to the fully mixed tank experiencing more of a temperature degradation during discharging compared to the stratified and plug flow model. For all three models the power generation during discharging followed the trend associated with the falling off of tank temperature. This resulted in the plug flow model having the most constant power generation, at the cost of not having as long of an extended power generation compared to the other two models.
The power generation of the plug flow was generally close in magnitude to the stratified tank. Although the plug flow model yielded some unpredictable results using higher flow rates and a larger solar field. Under these conditions, more run-time errors were prominent and the power generated was not always as desirable as expected. Between all three models, the plug flow model seemed to cause the most instability within the simulation under these conditions.

All three models also exhibited a greater magnitude of power generation with increasing discharging flow rate. This can be seen in the graphs in the Results section as well as in Appendix E.

Results for the stratified and plug flow model using different solar field sizes were typical in that a higher average temperature was observed using the larger field. The temperature distributions within each tank also yielded expected results. Results for the plug flow model were similar using the 1-hour tank with the two lower discharging flow rates.
CHAPTER 5

CONCLUSIONS

Two new thermal storage components were successfully created in IISiBat for use in TRNSYS. The implementation of these two storage components into a SEGS model proved to be more difficult than anticipated. Some insight for the modeling of different thermal storages with a SEGS model was gained, however much of the project was plagued with difficulties in obtaining results.

The most prominent source of these difficulties was not using the most current SEGS VI simulation that was developed. The SEGS VI model that was used was documented to contain an earlier version of the trough model and turbine controller. To further hamper the project, efforts to obtain information and updated components were met with little success.

The results that were obtained did support other researchers findings that to correctly model thermal storage (specifically for a SEGS), modeling should include thermal storage integrated in a SEGS. Surprisingly, the fully mixed model showed that it could maintain an extended power generation comparable to the stratified model at the expense of a lower maximum power generation. While the plug flow model had several difficulties in generating results, what was obtained indicated that a higher maximum power generation with a shorter
duration could be achieved. Extended power generation was also observed to be a function of discharging temperature and flow rate.

These results indicate that for this particular SEGS VI model, the fully mixed model would probably be the best selection if the objective for implementing thermal storage was to generate power for a long period without much of a concern for a high amplitude. This would indicate that precautions to reduce mixing within the tank would not have to be taken into the physical design of the storage. This would simplify the design of the storage system and could reduce cost. However, if the objective was to implement thermal storage for generating a high level of extended power with not too much concern for duration, the stratified or plug flow model would be the better selections for choosing a physical design for thermal storage with this SEGS model.

Using the program TRNSYS as a transient simulation tool for this project met with some success. TRNSYS does have the capabilities to model complex systems such as the SEGS VI model especially if the user is well versed in the operation of the TRNSYS engine. During this project, many revisions had to be made to the new storage components because not enough information was available in the TRNSYS manual to describe its more detailed operation\(^4\). When using TRNSYS with IISiBat for simple simulations that contained the new storage components, the process was very simple, user-friendly and straightforward.

\(^4\) Much of TRNSYS' operation was gained from technical support via e-mail.
However, when implemented into a more complex simulation system, initial strange results were obtained that indicated a better knowledge about TRNSYS' internal processes should be investigated. Because not much was available in the manual, a lot of time was invested in programming the new components to compensate for use into the complex SEGS VI model.

Recommendations

The results that were obtained from this project did indicate the usefulness of combining thermal storage into a SEGS model. Several improvements could be made to generate more of a spectrum of results than what was obtained. Most notably would be to use a current (if possible) SEGS model for integrated simulations.

Improvement of the Storage Controller logic could also be performed. While the current developed component was able to control charging and discharging cycles, more of a detailed control logic could be developed to better model the characteristics associated with thermal storage. By using a finalized version of the SEGS VI model may also help to understand what type of better storage controller logic to use.

Development of a cost analysis component in TRNSYS to evaluate the initial cost and LEC associated with a SEGS plant integrated with thermal storage would also be a beneficial tool for evaluating thermal storages.
APPENDIX A

STEC LIBRARY

The Solar Thermal Electric Components (STEC) library was created by DLR (German Aerospace Centre), Sun Lab/Sandia and IVTAN (Institute for High Temperatures of the Russian Academy of Science, Russia) in 1988 [8]. Many of the components in this library are needed in creating a solar electric generating system. In 2000, the University of Wisconsin, Madison validated several of these components by creating a model of the SEGS VI plant at Kramer Junction located in the Mohave Desert, California [6]. Only the solar side of the plant was modeled and several days of solar-only power generation data was compared to results obtained from their model. Agreement between the simulation and actual plant data was generally within 10%, although there was difficulty in modeling solar field flow rate during transient periods [6].

Currently there are no thermal storage components within the STEC library although there are several sensible thermal storage models included with the standard TRNSYS library [9], [15].
APPENDIX B

COMPONENT PARAMETERS, INPUTS AND OUTPUTS

The following figures show the parameter and input windows that is seen in IISiBat for the use of the Sensible Storage Modeler and the Storage Controller.

Some of the required user specified parameters and inputs are different depending upon which storage model is to be utilized. Parameters are variables that remain constant throughout the simulation compared to an input that can be constant or time-dependent within the simulation. Figure B.1 shows the window in IISiBat for entering information regarding parameters to the Sensible Storage Modeler.
Figure B.1  Parameters for the Sensible Storage Modeler Component

The storage type can be an integer from 1 through 3 that selects the storage model to be used during a simulation (1 – fully mixed model, 2 – stratified model and 3 – plug flow model). Parameters 2 and 3 are self-explanatory to describe the size of the cylindrical tank. Parameters 4 and 7 are only for the stratified model which allows a user to specify up to 50 nodes within the tank and an internal time step to promote stability by preventing the incoming flow rate to exceed the mass within a node. Parameters 5 and 6 are for calculating the energy, entropy and exergy within the tank that is above the delivery temperature but were not used for this project.
Figure B.2 Inputs for the Sensible Storage Modeler Component

The Input window in IISiBat is shown in Figure B.2 and contains three inputs. Input 1 or the Storage Mode comes from the Storage Controller component and controls whether the storage is in a charging, dwell or discharging cycle (1 – charging, 2 – dwell and 3 – discharging). Inputs 2 and 3 are also from the Storage Controller that relays the flow rate and temperature of the flow entering the tank.
APPENDIX C

OBSTACLES ENCOUNTERED

The following is a list of problems and concerns that arose during the work of this project.

1. Trough and Turbine Controller components in the SEGS VI model were determined not to be the most current.

2. Setting for the parameters in the SEGS VI model that was obtained may not have been set at the conditions at the actual SEGS VI plant.

3. Changing the calling order of component within TRNSYS sometimes produced different results. While sometimes non-convergence could explain some differing results, there were other situations that could not be explained by non-convergence (results showed convergence).

4. Care must be used in that correct units are passed to and from components. The user has to be aware that the units are matched correctly between components. TRNSYS has a subroutine that can be used to check for unit mis-matching, but it does not correct for it.

5. The TRNSYS manual was found to be good for an overview of the program and describes the components that come with TRNSYS (in the .dll) in sufficient detail. However, more detail about how the TRNSYS engine operates would be beneficial.
6. Simulating the SEGS VI model without any storage (unchanged) for a complete year resulted in several FORTRAN math run-time errors. These hourly time steps are: 64, 734, 785, 1265, 4404, 6089, 6108, 6566, 7528, 7816 and 8200.

7. Simulation runs using storage had a few periods in which errors occurred. This is summarized in the following list:

   a. Mixed model using 1-hr tank at 400,000 kg/hr with 20% larger solar field produced too many run time errors so a solar field increased by 10% was used instead.

   b. Stratified model using 1-hr tank at 500,000 kg/hr with a 20% larger solar field produced a convergence error in function THP (steam3 subroutine) so a solar field increased by 15% was used instead.

   c. Stratified model using 1-hr tank at 600,000 kg/hr with a 20% larger solar field produced a convergence error in function THP (steam3 subroutine) so only the last five days were simulated.

   d. Stratified model using 2-hr tank at 500,000 kg/hr with standard field produced a run-time error at hour 4819.5.

   e. Stratified model using 2-hr tank at 500,000 kg/hr with a 20% larger solar field produced a run-time error at hour 4722.5.

   f. Stratified model using 2-hr tank at 600,000 kg/hr with a 20% larger solar field produced many run-time errors. Only the last 4 days were simulated.
g. Plug model using 2-hr tank at 400,000 kg/hr with a 20% larger solar field caused run time errors. Only the last 4 days were simulated.

h. Plug model using 2-hr tank at 600,000 kg/hr with a standard solar field caused run time errors. Only the first 2 and last 4 days were simulated.
APPENDIX D

SEGS VI

The power generation and the temperature from the trough for the SEGS VI model without storage are shown in the following graphs. The power generation graph in Figure D.1 shows that day 2 experienced some cloud cover and day 5 was a cloudy day. Day 7 had the most solar radiation to produce the most power generation.

![Power Generation using No Storage](image)

Figure D.1 SEGS VI Power Generation for No Storage July 13-19
The temperature from the trough is shown in Figure D.2 for the SEGS VI model with no storage. Most of the days show a temperature higher than the set point of 350°C with the exception of day 5. This indicates that the solar field pump could not generate a high enough flow rate to maintain the set point temperature of the fluid out of the trough.

Figure D.2  SEGS VI Trough Temperature for No Storage July 13-19

Figure D.3 shows the SEGS VI model integrated with the two new thermal storage components as a Storage Macro. The Storage Macro was installed just outside of the HTF recirculation loop and just before the steam train.
Figure D.3  Full View of Storage Macro in SEGS VI Model
APPENDIX E

GRAPHICAL RESULTS

The following graphs are the remaining results that were generated during the study for this project. The first section is the power generation by model versus size of field for the 400,000 kg/hr and the 600,000 kg/hr discharging flow rates for all three models. The next section shows the average temperature versus size of field for the 400,000 kg/hr and the 600,000 kg/hr discharging flow rates for all three models. Following in the next section are graphs for the temperature distribution for each model using all three discharging flow rates of 400,000 kg/hr, 500,000 kg/hr and 600,000 kg/hr and for the 1-hour and 2-hour size tanks.

Comparison graphs are in the last two sections for power generation and average temperature. The power generation graph shows all three models including the case of no storage and the average temperature graph compares all three different storage models using the standard solar field size.

Most of the trends that were discussed in Chapter 4 can also be seen in the following power generation and average temperatures graphs. Data that is missing in some of the graphs are due to run-time errors. The temperature distributions for the three models were mostly as expected with the top of the tank as the hottest and the coolest at the bottom. The only exception was for the plug flow model for the larger flow rates where the simulations became unstable.
Power Generation by Model

**Figure E.1** Fully Mixed Power Generation 1-hour tank (400)

**Figure E.2** Fully Mixed Power Generation 1-hour tank (600)
Figure E.3  Fully Mixed Power Generation 2-hour tank (400)

Figure E.4  Fully Mixed Power Generation 2-hour tank (600)
Figure E.5  Stratified Power Generation 1-hour tank (400)

Figure E.6  Stratified Power Generation 1-hour tank (600)
Figure E.7  Stratified Power Generation 2-hour tank (400)

Figure E.8  Stratified Power Generation 2-hour tank (600)
Figure E.9  Plug Flow Power Generation 1-hour tank (400)

Figure E.10  Plug Flow Power Generation 1-hour tank (600)
Figure E.11  Plug Flow Power Generation 2-hour tank (400)

Figure E.12  Plug Flow Power Generation 2-hour tank (600)
Average Temperatures

12x16/400 Mixed Average Temperature vs. Field Size

- Standard
- 10% larger

Figure E.13  Fully Mixed Average Temperature 1-hour tank (400)

12x16/600 Mixed Average Temperature vs. Field Size

- Standard
- 20% larger

Figure E.14  Fully Mixed Average Temperature 1-hour tank (600)

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Figure E.15  Fully Mixed Average Temperature 2-hour tank (400)

Figure E.16  Fully Mixed Average Temperature 2-hour tank (600)
Figure E.17  Stratified Average Temperature 1-hour tank (400)

Figure E.18  Stratified Average Temperature 1-hour tank (600)
Figure E.19  Stratified Average Temperature 2-hour tank (400)

Figure E.20  Stratified Average Temperature 2-hour tank (600)

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Figure E.21  Plug Flow Average Temperature 1-hour tank (400)

Figure E.22  Plug Flow Average Temperature 1-hour tank (600)
Figure E.23  Plug Flow Average Temperature 2-hour tank (400)

Figure E.24  Plug Flow Average Temperature 2-hour tank (600)
Temperature Distributions

12x16/400 Stratified Temperature Distribution

Figure E.25 Stratified Temperature Distribution 1-hour tank (400)

12x16/500 Stratified Temperature Distribution

Figure E.26 Stratified Temperature Distribution 1-hour tank (500)

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Figure E.27 Stratified Temperature Distribution 1-hour tank (600)

Figure E.28 Stratified Temperature Distribution 2-hour tank (400)

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Figure E.29 Stratified Temperature Distribution 2-hour tank (500)

Figure E.30 Stratified Temperature Distribution 2-hour tank (600)
Figure E.31  Plug Flow Temperature Distribution 1-hour tank (400)

Figure E.32  Plug Flow Temperature Distribution 1-hour tank (500)

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Figure E.33  Plug Flow Temperature Distribution 1-hour tank (600)

Figure E.34  Plug Flow Temperature Distribution 2-hour tank (400)

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Figure E.35  Plug Flow Temperature Distribution 2-hour tank (500)

Figure E.36  Plug Flow Temperature Distribution 2-hour tank (600)
APPENDIX F

FORTRAN CODES

This section contains an example of a deck file generated using IIiSiBat and the FORTRAN coding for the Storage Controller Component and the Sensible Storage Modeler Component.

Deck File Example

VERSION 15
*******************************************************************************
*** TRNSYS input file (deck) generated by IIiSiBat 3
*** on Tuesday, October 28, 2003 at 11:34
*** from IIiSiBat project: C:\Documents and Settings\Jade\My Documents\THESIS\TRNSYS stuff\Sample.TPF
***
*** If you edit this file, use the File/Import TRNSYS Input File function in
*** IIiSiBat 3 to update the project.
***
*** If you have problems, questions or suggestions please contact your local
*** TRNSYS distributor or mailto:iiisibat@cstb.fr
***
*******************************************************************************
ASSIGN "\MOD3forUNLV\fullyear-original.LST" 6
*******************************************************************************
*** Control cards
*******************************************************************************
* START, STOP and STEP
CONSTANTS 3
START=5832
STOP=5856
STEP=.5
*SIMULATION Start time   End time   Time step
SIMULATION   START   STOP   STEP
* User defined CONSTANTS
VERSION 15
*
TOLERANCES .005 .005
*
limit
LIMITS 1000 1000 1100
*
DFQ 1
*
characters
WIDTH 80
*
LIST
*
NOLIST statement
* MAP statement
* Solver statement
SOLVER 0
*******************************************************************************
*** Units*******************************************************************************
*
* Model "Weather Reader" (Type 89)
*
UNIT 1 TYPE 89 Weather Reader
PARAMETERS 2
* 1 Mode
-2
* 2 Logical unit
13
*** External files
ASSIGN "\MOD3forUNLV\lasvegas.tm2" 13
*1 Which file contains the TMY2 weather information? |1000
*
* Model "RadProcessor" (Type 16)
*
UNIT 2 TYPE 16 RadProcessor
PARAMETERS 9
* 1 Horiz. radiation mode
4
* 2 Tracking mode
4
* 3 Tilted surface mode
3
* 4 Starting day
244
* 5 Latitude
36.06
* 6 Solar constant
4871.0
* 7 Shift in solar time
4.83
* 8 Not used
2
* 9 Solar time?
1
INPUTS 7
* Weather Reader: Global horizontal radiation -> Total radiation on horizontal surface
1,4
* Weather Reader: Direct normal radiation -> Direct normal beam radiation on horizontal
1,3
* Weather Reader: Time of last read -> Time of last data read
1,99
* Weather Reader: Time of next read -> Time of next data read
1,100
* [unconnected] Ground reflectance
0,0
* [unconnected] Slope of surface
0,0
* [unconnected] Azimuth of surface
0,0
*** INITIAL INPUT VALUES
0.0 0 0.0 1.0 0.2 0.0 0.0
*------------------------------------------------------------------------
* Model "Trough" (Type 196)
*
UNIT 3 TYPE 196 Trough
PARAMETERS 22
* 1 A - Loss coef.
70.75
* 2 B - Loss coef.
-0.00657
* 3 C - Loss coef.
-4.74981
* 4 Cw - Loss coef.
-1.904
* 5 D - Loss coef.
-0.06956
* 6 Clean Reflectivity
0.94
* 7 Broken Mirror Fraction
0.003
* 8 Length of SCA
47
* 9 Aperture Width of SCA
5.0
* 10 Focal Length of SCA
1.4
* 11 Rowspacing
12.5
* 12 Total Field Area
188000
* 13 Pump Max Power
5616000
* 14 Pump Max Flow Rate
1440000
* 15 Pump Power Coeff. 1
0.20175
* 16 Pump Power Coeff. 2
-0.8994
* 17 Pump Power Coeff. 3
1.692
* 18 Tank Heat Loss Rate at 275 C
2570000
* 19 Piping Heat Loss/Area at 343C
10
* 20 Field Tracking Parasitics/Area
0.86
* 21 Stow Energy for Each m2 Field Area
11250
* 22 Wind Speed Limit for Tracking
13.7
INPUTS 14
* [unconnected] Demanded Outlet Temperature
0,0
* [unconnected] Inlet Temperature Solar Field
0,0
* [unconnected] Cleanliness Solar Field
0,0
* [unconnected] Specific Heat HTF
0,0
* RadProcessor:Solar azimuth angle ->Sun Azimuth
2,3
* RadProcessor:Solar zenith angle ->Sun Zenith
2,2
* Weather Reader:Direct normal radiation ->DNI- Direct Normal Radiation
1,3
* Weather Reader:Wind velocity ->Wind Speed
1.7
* Weather Reader: Dry bulb temperature -> Ambient Temperature
1.5
* [unconnected] Tracking Fraction of Field
0.0
* [unconnected] Available Fraction of Field
0.0
* [unconnected] Night Flow Ratio (min Flow)
0.0
* [unconnected] Rampdown Time
0.0
* [unconnected] Rampdown Ratio
0.0
*** INITIAL INPUT VALUES
350 171 0.91 2.503 0 0 0 25 1.0 1.0 0.1 2.25 0.4
-----------------------------------------------
* Model "ExpTank" (Type 4)
*
UNIT 4 TYPE 4 ExpTank
PARAMETERS 26
* 1 Variable inlet positions
 2
* 2 Tank volume
 545.103531816633
* 3 Fluid specific heat
 2.36135417800591
* 4 Fluid density
 797.398603190876
* 5 Tank loss coefficient
 0.5
* 6 Height of node-1
 0.60960741282614
* 7 Height of node-2
 1.21921482565228
* 8 Height of node-3
 1.8288223847842
* 9 Height of node-4
 2.43842965130456
* 10 Height of node-5
 3.0480370641307
* 11 Height of node-6
 3.65764447695684
* 12 Height of node-7
 4.26725188978298
* 13 Auxiliary heater mode
 1
* 14 Node containing heating element -1
  1
* 15 Node containing thermostat -1
  1
* 16 Set point temperature for element-1
  55.0
* 17 Deadband for heating element-1
  5.0
* 18 Maximum heating rate of element -1
  0
* 19 Node containing heating element -2
  6
* 20 Node containing thermostat -2
  6
* 21 Set point temperature for element-2
  55.0
* 22 Deadband for heating element-2
  5.0
* 23 Maximum heating rate of element -2
  0
* 24 Not used (Flue UA)
  0.0
* 25 Not used (Tflue)
  20.0
* 26 Boiling point
  5000
INPUTS 7
* [unconnected] Hot-side temperature
  0,0
* [unconnected] Hot-side flowrate
  0,0
* Trough:Outlet Temperature Solar Field ->Cold-side temperature
  3,2
* Trough:Flow Rate Solar Field ->Cold-side flowrate
  3,1
* Weather Reader:Dry bulb temperature ->Environment temperature
  1,5
* [unconnected] Control signal for element-1
  0,0
* [unconnected] Control signal for element-2
  0,0
*** INITIAL INPUT VALUES
  45.0 0 20.0 0 22.0 0.0 0.0
DERIVATIVES 7
* 1 Initial temperature of node-1
  204
* 2 Initial temperature of node-2
204
* 3 Initial temperature of node-3
204
* 4 Initial temperature of node-4
204
* 5 Initial temperature of node-5
204
* 6 Initial temperature of node-6
204
* 7 Initial temperature of node-7
204
*----------------------------------------------------------------------

* Model "Tank Output" (Type 65)
*
UNIT 5 TYPE 65 Tank Output
PARAMETERS 10
* 1 Nb. of left-axis variables
2
* 2 Nb. of right-axis variables
2
* 3 Left axis minimum
0.0
* 4 Left axis maximum
1000.0
* 5 Right axis minimum
0.0
* 6 Right axis maximum
1000.0
* 7 Number of plots per simulation
1
* 8 X-axis gridpoints
7
* 9 Shut off Online w/o removing
0
* 10 Logical Unit for output file
-1
INPUTS 4
* ExpTank: Temperature to heat source -> Left axis variable-1
4,1
* [unconnected] Left axis variable-2
0,0
* ExpTank: Flowrate to heat source -> Right axis variable-1
4,2
* [unconnected] Right axis variable-2
0,0
*** INITIAL INPUT VALUES
Temperature label Flowrate label
LABELS 5
C kg/hr
Temperature
Power
Trough

END

Storage Controller FORTRAN Code

SUBROUTINE TYPE298 (TIME,XIN,OUT,T,DTDT,PAR,INFO,ICNTRL,*)
C************************************************************************
C Object: Storage Controller 1
C IISiBat Model: Type298
C
C Author: Jade Gaal
C Editor:
C Date: 7/3/2003 last modified: 10/27/2003
C
C This component works in conjunction with Type 299 storage model. It
determines what mode (StorMode) the storage should be in.
C  1 - Charging
C  2 - Dwell
C  3 - Discharging
C
C ***
C *** Model Parameters
C ***
C Desired Power  kW [0;+Inf]
C Desired Pressure  BAR [0;+Inf]
C Minimum Temp  C [-Inf;+Inf]
C Switch1  dimensionless [1;2]
C ***
C *** Model Inputs
C ***
C Power kW [0;+Inf]
C Pressure frm S.H.  BAR [0;+Inf]
C Flow from Trough  kg/hr [0;+Inf]
C Temp from Trough  C [0;500]
C Flow from S.T.  kg/hr [0;+Inf]
C Temp from S.T.  C [0;500]
C Charging Temp Out  C [0;500]
C Discharging Temp Out  C [0;500]

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C Pump Flowrate kg/hr [0;+Inf] !currently not used
C Pump Temperature C [0;500] !currently not used
C ***
C *** Model Outputs
C ***
C Storage Mode dimensionless [1;3]
C Flow kg/hr [0;+Inf]
C Temp C [-Inf;++Inf]
C Flow to S.T. kg/hr [0;+Inf]
C Temp to S.T. C [-Inf;++Inf]
C Flow to Trough kg/hr [-Inf;++Inf]
C Temp to Trough C [-Inf;++Inf]
C Specific Heat to ST kJ/kg.K [-Inf;++Inf]
C Desired Pump Flowrate kg/hr [0;++Inf]
C Return Split Function dimensionless [0;1]
C Reheater Split Function dimensionless [0;1]
C ***
C *** Model Derivatives
C ***
C (Comments and routine interface generated by IISiBat 3)
C*********************************************************
C STANDARD TRNSYS DECLARATIONS
DOUBLE PRECISION XIN,OUT
INTEGER NI,NP,ND,NO
PARAMETER (NI=10,NP=4,NO=11,ND=0)
INTEGER*4 INFO,ICNTRL
REAL T,DTDT,PAR,TIME
DIMENSION XIN(NI),OUT(NO),PAR(NP),INFO(15)
CHARACTER*3 YCHECK(NI),OCHECK(NO)
C MODEL DECLARATIONS
INTEGER Switch,Stormode,ContrlRsplit,PREVSTORMODE
REAL MinTemp,m1,m2,mass
C*********************************************************
C IF ITS THE FIRST CALL TO THIS UNIT, DO SOME BOOKKEEPING
IF (INFO(7).GE.0) GO TO 100
C FIRST CALL OF SIMULATION, CALL THE TYPECK SUBROUTINE TO CHECK THAT THE
C USER HAS PROVIDED THE CORRECT NUMBER OF INPUTS,PARAMETERS, AND DERIVS
INFO(6)=NO
INFO(9)=1
Flow=0
FlowtoST=0
Flowtotrough=0

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CALL TYPECK(1,INFO,N1,NP,ND)
RETURN 1
C END OF THE FIRST ITERATION BOOKKEEPING
C----------------------------------------------------------------------------
C GET THE VALUES OF THE PARAMETERS FOR THIS
COMPONENT
100 CONTINUE
  DesPower=PAR(1)
  Despress=PAR(2)
  MinTemp=PAR(3)
  Switch1=PAR(4)

C GET THE VALUES OF THE INPUTS TO THIS COMPONENT
  Power=XIN(1)*1000  !converting from input of MW to kW
  Press=XIN(2)
  FlowfrmTrough=XIN(3)  !input should be in kg/hr
  TempfrmTrough=XIN(4)  !input should be Celsius
  FlowfrmST=XIN(5)  !input should be in kg/hr
  TempfrmST=XIN(6)  !input should be Celsius
  CTout=XIN(7)  !input should be Celsius
  DTout=XIN(8)  !input should be Celsius
  FlowfrmPump=XIN(9)  !input should be kg/hr
  TempfrmPump=XIN(10)  !input should be Celsius

IF(Power.EQ.0) Power=0.001
C Make sure tank temp out are reset when iterations are performed
IF(INFO(7).LT.1) THEN
  PCTout=CTout
  PDTout=DTout
  PrevStormode=Stormode
ENDIF
IF(INFO(7).GE.1) THEN
  CTout=PCTout
  DTout=PDTout
ENDIF
C----------------------------------------------------------------------------
  eps = 0.001
t0 = 0
  Percentflow=1-DesPower/Power

  IF(Power.GT.Despower.AND.CTout+5.LE.Tempfrmtrough.AND.
  * PREVSTORMODE.EQ.1) THEN  !HOW LONG TO KEEP CHARGING
    !CHARGE STORAGE
    Stormode=1
    Flow=Flowfrmtrough*Percentflow
Temp=Tempfrmtrough
FlowtoST=Flowfrmtrough-Flow
TemptoST=Tempfrmtrough
Flowtotrough=Flow+FlowfrmST

* Calc to det. temp of mixing flows(from storage & ST to trough)
m1=Flow
m2=FlowfrmST
mass = m1+m2
cp_1= SpHeat(switch,CTout,Time)
cp_2= SpHeat(switch,TempfrmST,Time)
IF (mass.EQ.0) THEN
  temp=TempfrmST
  cp=cp_1
  GOTO 200
ENDIF

* Iteration for output cp
cp = (m1*cp_1+m2*cp_2)/mass
110 Continue

  cp_old = cp
  Temptotrough=t0+(m1*cp_1*(CTout-t0)+m2*cp_2*(TempfrmST
  *(Temptotrough
  *)
  IF(ABS(cp_old-cp).GT.eps) GOTO 110
  ContrlRsplit=0
  ContrlReheatersplit=1

ELSEIF(Power.GT.Despower.AND.DTout+.5.LE.Tempfrmtrough.AND. PREVSTORMODE.NE.1) THEN !WHEN TO START
  Stormode=1
  Flow=Flowfrmtrough*Percentflow
  Temp=Tempfrmtrough
  FlowtoST=Flowfrmtrough-Flow
  TemptoST=Tempfrmtrough
  Flowtotrough=Flow+FlowfrmST

  * Calc to det.
m1=Flow
m2=FlowfrmST
mass = m1+m2
cp_1= SpHeat(switch,CTout,Time)
cp_2= SpHeat(switch,TempfrmST,Time)
IF (mass.EQ.0) THEN
  temp=TempfrmST
  cp=cp_1
  GOTO 200
ENDIF

* Iteration for output cp
cp = (m1*cp_1+m2*cp_2)/mass

120 Continue

cp_old = cp
Temptotrough=t0+(m1*cp_1*(CTout-t0)+m2*cp_2*(TempfrmST
*t0))/(mass*cp)

IF(ABS(cp_old-cp).GT.eps) GOTO 120

ELSEIF(Press.LE.Despress.AND.DTout.GT.MinTemp
*AND.Tempfrmtrough.LT.MinTemp.AND.PREVSTORMODE.NE.3)THEN

!DISCHARGE STORAGE (WHEN TO START)
Stormode=3
Temp=TempfrmPump

ELSEIF(PREVSTORMODE.NE.3.AND.FLOW.EQ.0) THEN
FLOW=400000
ELSE
IF(INFO(7).LT.1) THEN
PREVFLOW=FLOW
ENDIF
ENDIF
IF(FLOW.EQ.0) FLOW=PREVFLOW
FlowtoST=Flow
TemptoST=DTout
FlowtoTrough=FlowfrmST
TemptoTrough=TempfrmST

ELSEIF(DTout.GT.MinTemp.AND.PREVSTORMODE.EQ.3) THEN

!WHEN TO STOP DISCHARGING
Stormode=3
Temp=TempfrmPump

ELSEIF(PREVSTORMODE.NE.3.AND.FLOW.EQ.0) THEN
FLOW=400000
ELSE
IF(INFO(7).LT.1) THEN
PREVFLOW=FLOW
ENDIF
ENDIF
IF(FLOW.EQ.0) FLOW=PREVFLOW
Flow=Flow*ABS(Despress/Press)
TemptoST=DTout !temp frm discharging storage
FlowtoTrough=FlowfrmST !flow to HTF Mix to trough mixer
TemptoTrough=TempfrmST !flow to HTF Mix to trough mixer
ContrlRsplit=1
ContrlReheatersplit=0.875

ELSE
!DWell
Stormode=2
Flow=0
Temp=0
FlowtoST=Flowfrmtrough
TemptoST=Tempfrmtrough
Flowtotrough=FlowfrmST
Temptotrough=TempfrmST
ContrlRsplit=0
ContrlReheatersplit=1

ENDIF

* Specific Heat to ST
Cp= SpHeat(switch,TemptoST,Time)

C----------------------------------------------------------------------------
C SET THE OUTPUTS
200 CONTINUE
C Storage Mode
OUT(1)=Stormode
C Flow in or out of storage tank (kg/hr)
OUT(2)=Flow
C Temp into storage tank (C)
OUT(3)=Temp
C Flow to Steam Train (kg/hr)
OUT(4)=FlowtoST
C Temp to Steam Train (C)
OUT(5)=TemptoST
C Flow to trough (kg/hr)
OUT(6)=Flowtotrough
C Temp to trough (C)
OUT(7)=Temptotrough
C Specific Heat to ST (kJ/kg K)
OUT(8)=Cp
C Desired Pump Flowrate
OUT(9)=DTOUT !currently not used
C Return Split Function
OUT(10)=ContrlRsplit
Reheater Split Function

OUT(11)=ContrlReheatersplit

RETURN 1
END

FUNCTION SpHeat(sw,te,Time)
INTEGER sw
REAL te
IF (te.LT.0.OR.te.GT.450) THEN
  WRITE (6,*) ' Warning! Type 298 HTF mix: Output temp is
  c out of bound at',Time',Time
  c_p=1.0
  RETURN
ENDIF

c switch to right branch
1  = Santotherm VP1
2 = Syltherm 800
IF (sw.GT.1) GOTO 250

Calculation for Santotherm VP1
  c_p=8.3E-7*te**3+4.677E-4*te**2+2.6441*te+1507
  c_p = c_p/1000. ! output in kJ/kg K
  Goto 280

Calculation for Syltherm 800
250 Continue
  c_p=1E-6*te**2+1.7075*te+1575
  c_p = c_p/1000. ! output in kJ/kg K

280 CONTINUE
SpHeat = c_p
RETURN
END

Sensible Storage Modeler FORTRAN Code

SUBROUTINE TYPE299 (TIME,XIN,OUT,T,DTDT,PAR,INFO,ICNTRL,*)
C**************************************************************
C Object: Sensible Storage Evaluation Component
C IISiBat Model: Type 299
C
C Author: Jade Gaal
C Editor:
C Date: 1/27/2003 last modified: 10/13/2003
C
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This component is used to evaluate three different types of sensible storage in use with a solar power generation system. A systems designer can determine which type of storage model provides the best performance for a given solar generation system.

*** Model Parameters

- Storage Type: dimensionless [1;3]
- Tank Height: m [0;100]
- Tank Diameter: m [0;100]
- Number of Nodes: dimensionless [0;100]
- Delivery Temperature: C [-Inf;700]
- Ref. Temperature: C [-Inf;700]
- Internal Timestep: s [0;+Inf]

*** Model Inputs

- Storage Mode: dimensionless [1;3]
- Flow rate: kg/hr [0;+Inf]
- Temperature: C [0;700]

*** Model Outputs

- Performance: dimensionless [0;1] (currently not used)
- Energy: kJ [-Inf;+Inf] (currently not used)
- Entropy: kJ [-Inf;+Inf] (currently not used)
- Exergy: kJ [-Inf;+Inf] (currently not used)
- Average Temp: C [0;500]
- Charging Temp Out: C [0;500]
- Discharging Temp Out: C [0;500]
- Charging Flow: kg/hr [0;+Inf]
- Discharging Flow: kg/hr [0;+Inf]

*** Model Derivatives

(Comments and routine interface generated by IISiBat 3)

************ STANDARD TRNSYS DECLARATIONS

DOUBLE PRECISION XIN,OUT
INTEGER NI,NP,ND,NO
PARAMETER (NI=3,NP=7,NO=9,ND=0)
INTEGER*4 INFO,ICNTRL
REAL T,D TDT,PAR,T I ME
DIMENSION XIN(NI),OUT(NO),PAR(NP),INFO(15)
CHARACTER*3 YCHECK(NI),OCHECK(NO)

MODEL DECLARATIONS

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INTEGER Stormode, Stortype, IWARN, PREVN
REAL Nodes, FullyOut(4), PTs(100), Ts(100)
REAL StratOut(5), PerStratOut(5), PTemp(50), Temp(50)
REAL S, TIME0, TFINAL, DELT, Segmass(50), PSegmass(50)
INCLUDE '../INCLUDE/PARAM.INC
COMMON/STORE/NSTORE, IAV, S(NUMSTR)
COMMON /SIM/ TIME0, TFINAL, DELT, IWARN

C-------------------------------------------
C IF ITS THE FIRST CALL TO THIS UNIT, DO SOME
BOOKKEEPING
IF (INFO(7).GE.0) GO TO 100
C FIRST CALL OF SIMULATION, CALL THE TYPECK
SUBROUTINE TO CHECK THAT THE
C USER HAS PROVIDED THE CORRECT NUMBER OF
INPUTS, PARAMETERS, AND DERIVS
INFO(6)=NO
INFO(9)=1
INFO(10)=202
Avetemp=250
CTout=250
DTout=250
FLOWENERGY=0
N=1 !Initial # for plug flow
PREVN=N
FullVol=PAR(2)*0.25*3.14159*(PAR(3))**2
FullDensity=1067.342-0.588701*125-0.00088586*125**2
SegMass(1)=FullVol*FullDensity

* INTIIALIZING TANK TEMPERATURES
S(203)=523.15 !fully mixed
DO 10 i=1,100 !stratified
   S(203+i)=523.15
10 CONTINUE
S(305)=523.15 !Initializing plug flow

CALL TYPECK(1,INFO,NI,NP,ND)
RETURN 1
C END OF THE FIRST ITERATION BOOKKEEPING
C-------------------------------------------
C GET THE VALUES OF THE PARAMETERS FOR THIS
COMPONENT
100 CONTINUE
Stortype=PAR(1)
HTotal=PAR(2)
Diam=PAR(3)
Nodes=PAR(4)
Tdel=PAR(5)
Tref=PAR(6)
Intdeltat=PAR(7)

C GET THE VALUES OF THE INPUTS TO THIS COMPONENT
StorMode=XIN(1)
Flow=XIN(2)/3600 convert to kg/s from kg/hr
Tin=XIN(3)+273.15 !convert to K from C

C---- MAIN PROGRAM---------------------------------------------
Iter=DELT*3600/Intdeltat !COUNTER FOR DO LOOP TO MEET
SPECIFIED SIMULATION TIME (all 3 models need)

FULLY MIXED MODEL
*****************************************************************************
IF(Stortype.EQ.1) THEN
* RECALLING TEMPERATURES FROM PREVIOUS TIMESTEP
 Storagetemp1=S(203)
* Make sure tank is reset to prev timestep when iterations are
 performed during a given timestep
 IF(INFO(7).LT.1) PStoragetemp1=Storagetemp1
 IF(INFO(7).GE.1) Storagetemp1=PStoragetemp1
 CTout=Storagetemp1-273.15
 !Setting temps in case dwell occurs
 DTout=Storagetemp1-273.15
 CALL FullyMixed(Flow,Tin,Stormode,Storagetemp1,Iter,Par,
 FullyOut,DELT)
 * STORING TEMPERATURE FOR NEXT TIMESTEP
 S(203)=Storagetemp1 ! (K)
 Avetemp=Storagetemp1-273.15 !converting from K to C
 Energy=FullyOut(1) ! (kJ)
 Entropy=FullyOut(2) ! (kJ)
 Exergy=FullyOut(3) ! (kJ)
 Perf=FullyOut(4) ! (Dimensionless)
 *
 SETTING THE CHARGING/DISCHARGING FLOWS & TEMP
 IF(Stormode.EQ.1) THEN !Charging
 CFlow=Flow*3600 ! converting to kg/hr from kg/s
 DFlow=0
 ENDIF
 IF(Stormode.EQ.2) THEN !Dwell
 CFlow=0
 DFlow=0
 ENDIF
 IF(Stormode.EQ.3) THEN !Discharging
 CFlow=0
 DFlow=Flow*3600 ! converting to kg/hr from kg/s

ENDIF
CTout=Avetemp
DTout=Avetemp

STRATIFIED MODEL
*******************************************************************************
ELSEIF(Stortype.EQ.2) THEN
*
RECALLING TEMPERATURES FROM PREVIOUS TIMESTEP
DO 30 i=1,Nodes
   Ts(i)=S(203+i)
30 CONTINUE
*
Make sure tank is reset to prev timestep for iterations
IF(INFO(7).LT.1) PTs=Ts
IF(INFO(7).GE.1) Ts=PTs
*
IF(StorMode.EQ.2) THEN !If Storage is dwelling, all remains same
   CFlow=0
   DFlow=0
   GOTO 200
ENDIF
CALL Stratified(Flow,Tin,Stormode,Ts,Iter,Par,StratOut,Time)
*
STORING CURRENT TEMPERATURE FOR NEXT TIMESTEP
DO 50 i=1,Nodes !(K)
   S(203+i)=Ts(i)
50 CONTINUE
Energy=StratOut(1)
Entropy=StratOut(2)
Exergy=StratOut(3)
Perf=StratOut(4)
Avetemp=StratOut(5)
*
SETTING THE CHARGING/DISCHARGING FLOWS OUT & TEMP OF TOP & BOTTOM NODE
IF(Stormode.EQ.1) THEN !Charging
   CFlow=Flow*3600 !converting to kg/hr from kg/s
   DFlow=0
   CTout=Ts(Nodes)-273.15 !converting from K to C
   DTout=Ts(1)-273.15 !converting from K to C
ENDIF
IF(Stormode.EQ.3) THEN !Discharging
   CFlow=0
   DFlow=Flow*3600 !converting to kg/hr from kg/s
   CTout=Ts(Nodes)-273.15 !converting from K to C
   DTout=Ts(1)-273.15 !converting to K from C
ENDIF

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IF(Stormode.EQ.2.OR.Flow.LE.0) THEN
    CFlow=0
    DFlow=0
    CTout=Ts(Nodes)-273.15 !converting from K to C
    DTout=Ts(1)-273.15 !converting to K from C
ENDIF

PLUG FLOW MODEL

ELSE

* RECALLING TEMPERATURES FROM PREVIOUS TIMESTEP
DO 40 i=1,N
    Temp(i)=S(304+i)
40 CONTINUE

C Make sure tank is reset to prev timestep for iterations
IF(INFO(7).LT.1) THEN
    PTemp=Temp
    PREVN=N
    PSegmass=Segmass
ENDIF
IF(INFO(7).GE.1) THEN
    Temp=PTemp
    N=PREVN
    Segmass=PSegmass
ENDIF

CALL PerfStratified(Flow,Tin,Stormode,Temp,DELT,Par,
PerStratOut,Time,N,SegMass)

STORING CURRENT TEMPERATURE FOR NEXT TIMESTEP
Energy=PerStratOut(1)
Entropy=PerStratOut(2)
Exergy=PerStratOut(3)
Perf=PerStratOut(4)
Avetemp=PerStratOut(5)
DO 120 i=1,N ! (K)
    S(304+i)=Temp(i)
120 CONTINUE

SETTING THE CHARGING/DISCHARGING FLOWS OUT & TEMP
OF TOP & BOTTOM NODE
IF(Stormode.EQ.1) THEN ! Charging
    CFlow=Flow ! already in kg/hr
    DFlow=0
    CTout=Temp(N)-273.15 ! converting from K to C
    DTout=Temp(1)-273.15 ! converting from K to C
ENDIF
IF(Stormode.EQ.3) THEN ! Discharging
    CFlow=0
IF(STORMODE.EQ.0) THEN
  CFlow=0
  DFlow=0
  CTout=Temp(N)-273.15 !converting from K to C
  DTout=Temp(1)-273.15 !converting to K from C
ENDIF
IF(Flow.LE.0) THEN
  CFIow=0
  DFIow=0
  CTout=Temp(N)-273.15 !converting from K to C
  DTout=Temp(1)-273.15 !converting to K from C
ENDIF
ENDIF

IF(STORMODE.EQ.1) THEN
  CPIN=1.500044+0.00276912*(Tin-273.15)-1.3e-7*(Tin-273.15)**2
  !Temp has to be in C (from Type 151)
  FLOWENERGY=FLOW*3600*DELT*CPIN*Tin
ELSEIF(STORMODE.EQ.3) THEN
  CPOUT=1.500044+0.00276912*DTout-1.3e-7*DTout**2
  !Temp has to be in C (from Type 151)
  FLOWENERGY=FLOW*3600*DELT*CPOUT*DTout
ELSE
  FLOWENERGY=0
ENDIF

C--------------------------------------------------------------------------
C SET THE OUTPUTS
200 CONTINUE
C Performance
  OUT(1)=Perf !dimensionless
C Energy (not currently used)
  OUT(2)=FLOWENERGY !should be in kJ
C Entropy
  OUT(3)=Entropy !should be in kJ
C Exergy
  OUT(4)=Exergy !should be in kJ
C Average Temp
  OUT(5)=Avetemp !already in C
C Charging Temp Out
  OUT(6)=CTout !already in C
C Discharging Temp Out
  OUT(7)=DTout !already in C
C Charging Flow
  OUT(8)=CFlow !already in kg/hr
C Discharging Flow
  OUT(9)=DFlow !already in kg/hr

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RETURN 1
END

****** FULLY MIXED
*********************************************************************************************
SUBROUTINE FullyMixed(Mass,Tin,Stormode,Tank,Iter,Par,FullyOut,
* DELT)
INTEGER Stormode
REAL Mass,Masst,FullyOut(4),Par(7)
C ***
C *** Model Parameters
C ***
C Area m^2 Cross sectional area of tank
C Cp kJ/kg*K Specific heat of tank
C Cpin kJ/kg*K Specific heat of incoming flow
C Delt hr simulation timestep
C Density kg/m^3 Density of fluid
C Diam m Diameter of tank
C Energy1 kJ
C Entropy1 kJ
C Exergy1 kJ
C Fullyout() results array back to main program
C HTotal m Height of tank
C Mass kg/s Mass flow rate into tank
C Masst kg Mass in the storage tank
C Perfi dimensionless Storage performance ra
C StorMode dimensionless Storage mode (1-Charging,2-
Dwell,3-Discharging)
C Tank K Temperature of Fully Mixed Tank
C TDel K Delivery temperature
C Tin K Temperature into tank
C Tref K Reference temperature
C Vol m^3 Volume of storage tank

HTotal=Par(2)
Diam=Par(3)
Tdel=Par(5)+273.15
Tref=Par(6)+273.15
Area=0.25*3.14159*Diam**2
Vol=Area*HTotal

Cpin=1.500044+0.00276912*(Tin-273.15)-1.3e-7*(Tin-273.15)**2
!Temp has to be in C (from Type 151)
Cp=1.500044+0.00276912*(Tank-273.15)-1.3e-7*(Tank-273.15)**2
!Temp has to be in C (from Type 151)
Density=1067.342-0.588701*(Tank-273.15)-0.00088586*(Tank-273.15)**2
!Temp has to be in C (from Type 151)
Masst=Vol*Density

*----- MAIN SECTION -----------------------------------------------
IF(STORMODE.EQ.2.OR.MASS.LE.0) GOTO 10
    !Dwell mode or
    NO FLOW INTO TANK

* NEW TEMPERATURE
Tank=Tank+Delt*3600/(Masst*Cp)*(Mass*Cpin*(Tin-Tank))
Cp=1.500044+0.00276912*(Tank-273.15)-1.3e-7*(Tank-273.15)**2
!Temp has to be in C (from Type 151)

* THERMODYNAMIC PROPERTIES (kJ)
10 Energy1=Masst*Cp*(Tank-Tdel)
    IF (Energy1.LT.0) Energy1=0
    Entropy1=Tref*Masst*Cp*LOG(Tank/Tdel)
    IF (Entropy1.LT.0) Entropy1=0
    Exergy1=Energy1-Entropy1

* PERFORMANCE PARAMETER
Perf1=0
    IF (Energy1.NE.0) Perf1=Exergy1/Energy1

* SET OUTPUTS TO RETURN
    FullyOut(1)=Energy1
    FullyOut(2)=Entropy1
    FullyOut(3)=Exergy1
    FullyOut(4)=Perf1
RETURN
END

***** STRATIFIED ******************************************
SUBROUTINE Stratified(Mass,Tin,Stormode,Ts,Iter,Par,StratOut,Time)

INTEGER Stormode
REAL Mcin,Mdin,Kfluid(100),Cp(100),Density(100),Massn(100)
REAL AV(100),E(100),S(100),A(100,100),B(100),X(100),Ts(100)
REAL StratOut(5),Par(7),Mass

C *** Model Parameters
C ***
C A Coefficient matrix for Gauss-Seidel
C Area m^2 Cross sectional area of tank
C AV() KJ Entropy of node
C Avetemp C average temperature of tank

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C B Coefficient matrix for Gauss-Seidel
C Cp() kJ/kg*K Specific heat of node
C Delta_x m Distance between nodes
C Density() kg/m^3 Density of node
C Diam m Diameter of tank
C E() kJ Energy of node
C Energy2 kJ Energy of tank
C Entropy2 kJ Entropy of tank
C Exergy2 kJ Exergy of tank
C Flow kg/s flow rate into tank within internal timestep
C HTotal m Height of tank
C Iter dimensionless Counter for DO LOOP
C Intdeltat s Internal timestep
C Kfluid() W/(m*K) thermal conductivity of node
C Mass kg/s Mass flow rate
C Massn() kg Mass of fluid in each node
C Maxit dimensionless Maximum iterations for GS
C Mein kg/s Charging mass flow rate
C Mdin kg/s Discharging mass flow rate
C Nodes dimensionless # of nodes in storage tank
C Perf2 dimensionless Storage performance rating
C S() kJ Entropy of node
C StorMode Storage mode (1-Charge,2-Dwell,3-Discharge)
C Tcin K Temperature of water during charging
C Tdin K Temperature of water during discharging
C Tdel K Delivery temperature
C Tin K Temperature into tank
C Tol Tolerance for Gauss Seidel iterations
C Tout K Temperature out of tank
C Tref K Reference temperature
C Ts() K Temperatures of each node (array)
C Vol m^3 Volume of storage tank
C X K Temperature directly from Gauss Seidel

HTotal=PAR(2)
Diam=PAR(3)
Nodes=PAR(4)
Tdel=PAR(5)
Tref=PAR(6)
Intdeltat=PAR(7)
Tol=0.00005
Maxit=100
Delta_x=HTotal/Nodes
Area=0.25*3.14159*Diam**2
Vol=Area*HTotal
*--- MAIN SECTION ---------------------------------------------------------------

* Set fluid properties and mass
DO 10 j=1,Nodes
   Kfluid(j)=(9E-12)*(Ts(j)**3)-(2E-7)*(Ts(j)**2)+2E-5*Ts(j) +0.1475
   !THIS IS FROM Monsanto's PROGRAM (Temps have to be in K)
   Cp(j)=1.500044+0.00276912*(Ts(j))-273.15)-1.3e-7*(Ts(j)-273.15)**2
   !Temp has to be in C (from Type 151)
   Density(j)=1067.342-0.588701 *(Ts(j))-273.15)-0.00088586*(Ts(j)-273.15)**2
   !Temp has to be in C (from Type 151)
   Massn(j)=(Vol*Density(j))/Nodes
10 CONTINUE

IF(STORMODE.EQ.2.OR.MASS.LE.0) GOTO 105
DO 100 n=1,lter
   Things change if the flow is up or down
   IF(Stormode.EQ.3) THEN
      !DISCHARGING
      DO 20 l1=1,Nodes
         IF (l1.EQ.1) THEN
            !Top Node
            A(1,1)= -Kfluid(1)*Area/Delta_x-Mass*CP(1)-Massn(1)*Cp(1)/Intdeltat
            A(1,2)= Mass*Cp(1 )+Kfluid(1)*Area/Delta_x
            B(1 )= -Massn(1)*Cp(1)*Ts(1)/Intdeltat
         ELSE IF (II .EQ.Nodes) THEN
            !Bottom Node
            A(Nodes, Nodes)= -Kfluid(Nodes)*Area/Delta_x-Mass*Cp(Nodes)-Massn(Nodes)*Cp(Nodes)/Intdeltat
            A(Nodes,Nodes-1 )= Kfluid(Nodes)*Area/Delta_x
            B(Nodes)= Mass*Cp(Nodes)*Tin-Massn(Nodes)*Cp(Nodes)*Ts(Nodes)/Intdeltat
         ELSE
            !Interior Node
            A(l1,11 )= -2*Kfluid(l1)*Area/Delta_x-Mass*Cp(l1)
            Massn(l1)*Cp(l1)/Intdeltat
            A(l1,l1+1)= Mass*Cp(l1)+Kfluid(l1)*Area/Delta_x
            A(l1,l1-1)= Kfluid(l1)*Area/Delta_x
            B(l1 )= -Massn(l1)*Cp(l1)*Ts(l1)/Intdeltat
         END IF
      20 CONTINUE
   ELSE
      !CHARGING
      DO 30 l1=1,Nodes

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IF (I1.EQ.1) THEN
! Top Node
A(1,1) = -Kfluid(1)*Area/Delta_x - Mass*Cp(1) -
          Massn(1)*Cp(1)/Intdeltat
A(1,2) = Kfluid(1)*Area/Delta_x
B(1) = -Massn(1)*Cp(1)*Ts(1)/Intdeltat - Mass*Cp(1)*
        Tin
ELSE IF (I1.EQ.Nodes) THEN
! Bottom Node
A(Nodes,Nodes) = -Kfluid(Nodes)*Area/Delta_x -
                  Massn(Nodes)*Cp(Nodes)/Intdeltat - Mass*N
                  *Cp(Nodes)
A(Nodes,Nodes-1) = fluid(Nodes)*Area/Delta_x + Mass*%
                   Cp(Nodes)
B(Nodes) = -Massn(Nodes)*Cp(Nodes)*Ts(Nodes)/Intdeltat
ELSE
! Interior Node
A(I1,I1) = -2*Kfluid(I1)*Area/Delta_x - Mass*Cp(I1) -
            Massn(I1)*Cp(I1)/Intdeltat
A(I1,I1+1) = Kfluid(I1)*Area/Delta_x
A(I1,I1-1) = fluid(I1)*Area/Delta_x + Mass*Cp(I1)
B(I1) = -Massn(I1)*Cp(I1)*Ts(I1)/Intdeltat
END IF

30 CONTINUE
END IF

* Begin Gauss-Seidel Solution
ERRMAX = TOL + 1.0
COUNT = 0
DO 50 I1=1,NODES
   X(I1) = 0.0
50 CONTINUE
55 IF ((COUNT.LT.MAXIT).AND.(ERRMAX.GT.TOL)) THEN
   ERRMAX = 0.0
   DO 70 I1=1,NODES
      SUM = 0.0
      DO 60 J1=1,NODES
         IF (J1.NE.I1) SUM = SUM + A(I1,J1)*X(J1)
60 CONTINUE
      XNEW = (B(I1) - SUM) / A(I1,I1)
      ERROR = ABS(XNEW - X(I1))
      IF (ERROR.GT.ERRMAX) ERRMAX = ERROR
      X(I1) = XNEW
70 CONTINUE
   COUNT = COUNT + 1
   GO TO 55

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END IF
IF (COUNT.GE.MAXIT) THEN
  PRINT*, 'NUMBER OF ITERATIONS EXCEEDED LIMIT'
END IF
TS = X

*---- FLUID PROPERTY CALCULATIONS BASED UPON TEMPERATURE -------
  DO 80 j=1,Nodes
    Kfluid(j)=(9E-12)*(Ts(j)**3)-(2E-7)*(Ts(j)**2)+2E-5*Ts(j)+0.1475 !THIS IS FROM Monsanto's PROGRAM
                     (Temps in K)
    Cp(j)=1.500044+0.00276912*(Ts(j))-273.15)-1.3e-7*(Ts(j)-
                         273.15)**2 !Temp has to be in C (from Type 151)
    Density(j)=1067.342-0.588701 *(Ts(j))-273.15)-0.00088586*
               (Ts(j)-273.15)**2 !Temp has to be in C (Type 151)
    Massn(j)=(Vol*Density(j))/Nodes
  80 CONTINUE

***** CHECK TO SEE IF FLOWRATE 'WASHES OUT' MASS IN NODE (Internal
        Timestep) ****************************
C    Check node 1 only since it will have the least amount of mass due to the
      highest temperature
      IF(Massn(1).LT.Mass*Intdeltat) THEN
      WRITE (6,*) ' Warningl Type 299 Flowrate washed out
      c mass in node 1 internal timestep','Time',Time
      GOTO 105
      ENDIF

******

******************************************************************************************************************

**

100 CONTINUE
* THERMODYNAMIC PROPERTIES
*    Energy,Entropy and Exergy for each node
105 DO 110 kk=1,Nodes
    E(kk)=Massn(kk)*Cp(kk)*(Ts(kk)-Tdel)
    IF (E(kk).LE.0) E(kk)=0
    S(kk)=Tref*Massn(kk)*Cp(kk)*LOG(Ts(kk)/Tdel)
    IF (S(kk).LE.0) S(kk)=0
    AV(kk)=E(kk)-S(kk)
110 CONTINUE
*    Energy,Entropy and Exergy for tank
    Energy2=0
    Entropy2=0
    Exergy2=0
    DO 120 i=1,Nodes
        Energy2=Energy2+E(i)
        Entropy2=Entropy2+S(i)
Exergy2 = Exergy2 + AV(i)

* PERFORMANCE PARAMETER
Perf2 = 0
Perf2 = Exergy2 / Energy2

* Average temperature of tank
Avetemp2 = 0
DO 125 i = 1, Nodes
   Avetemp2 = Avetemp2 + Ts(i)
125 CONTINUE
Avetemp2 = (Avetemp2 / Nodes) - 273.15

StratOut(1) = Energy2
StratOut(2) = Entropy2
StratOut(3) = Exergy2
StratOut(4) = Perf2
StratOut(5) = Avetemp2
RETURN
END

****** PERFECTLY STRATIFIED ********************************************
SUBROUTINE PerfStratified(Massin, Tin, Stormode, Temp, DELT, Par,
PerfStratOut, Time, N, Segmass)

C *** Model Parameters
C ***
C Area m^2 Cross sectional area of tank
C Avetemp C average temperature in tank
C Cp() kJ/kg*K Specific heat of node
C Delt hrs simulation timestep
C Density() kg/m^3 Density of segment
C Densityin kg/m^3 Density of incoming fluid
C Diam m Diameter of tank
C Energy3 kJ
C Entropy3 kJ
C Exergy3 kJ
C HTotal m Height of tank
C Iter Counter for Do Loop
C Massin kg/s Mass flow rate
C Mass() kg Mass of fluid in each segment
C Mcin kg/s Charging mass flow rate

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C Mnin kg/s Discharging mass flow rate
C N dimensionless number of segments in tank
C Perf3 dimensionless Storage performance rating
C StorMode Storage mode (1-Charge, 2-Dwell, 3-Discharge)
C Tank K Temperature for Fully Mixed Tank
C Tb() K Temperature of tank at timestep before
C Tcin K Temperature of water during charging
C Td in K Temperature of water during discharging
C Tdel K Delivery temperature
C Temp() K Temperature of nodes in current timestep
C Thermcond() W/(m*K) thermal conductivity of segment
C Tin K Temperature into tank
C Tref K Reference temperature
C Vol m^3 Volume of each segment
C Vflow m^3/s Volumetric flow rate of incoming fluid

HTotal=PAR(2)
Diam=PAR(3)
Tdel=PAR(5)+273.15
Tref=PAR(6)+273.15
EPS=0.1
Area=0.25*3.14159*Diam**2
Densityin=1067.342-0.588701*(Tin-273.15)-0.00088586*(Tin-273.15)**2
    !Temp has to be in C (from Type 151)
Massin=Massin*3600 !Mass into tank in kg/hr
IF(Massin.LE.0) GOTO 98

DO 30 i=1,N
    Thermcond(i)=(9E-12)*(Temp(i)**3)-(2E-7)*(Temp(i)**2)+2E-5
    !THIS IS FROM Monsanto's PROGRAM (Temps have to be in K)
    *Temp(i)+0.1475
    Cp(i)=1.500044+0.00276912*(Temp(i)-273.15)-1.3e-7*(Temp(i)+-273.15)**2
    !Temp has to be in C (from Type 151)
    Density(i)=1067.342-0.588701*(Temp(i)-273.15)-0.00088586*(Temp(i)-273.15)
    + Temp(i)-273.15)**2
    Delta_x(i)=SegMass(i)/Density(i)/Area
30 CONTINUE

IF(STORMODE.EQ.2) GOTO 98
   !Dwell mode
   NEW TEMPERATURES DUE TO CONDUCTION
   IF(N.NE.1) THEN  !If more than 1 segment then calc top node &
       bottom node
       TOP SEGMENT
       AA=-(Thermcond(2)*Area)/(SegMass(1)*Cp(1)*
+ delta_x(1))
BB=(Thermcond(2)*Area*Temp(2))/(SegMass(1)*Cp(1)*delta_x(1))
TI=Temp(1)
CALL DIFSEQ(TIME,AA,BB,TL,TF,TBAR)
Temp(1)=TF
IF(N.GT.2) THEN !Only calculate for an interior
    * INTERIOR SEGMENTS
    DO 40 i=2,N-1
        AA=-(Thermcond(i-1)+Thermcond(i+1))*(Area/(SegMass(i)*Cp(i)*delta_x(i))
        + BB=(Thermcond(i-1)*Temp(i-1)+Thermcond(i+1)*Temp(i+1))*(Area/(SegMass(i)*Cp(i)*delta_x(i))
        TI=Temp(i)
        CALL DIFSEQ(TIME,AA,BB,TL,TF,TBAR)
        Temp(i)=TF
    40 CONTINUE
ENDIF
* BOTTOM SEGMENT
AA=-(Thermcond(N-1)*Area)/(SegMass(N)*Cp(N)*delta_x(N))
BB=(Thermcond(N-1)*Area*Temp(N-1))/(SegMass(N)*Cp(N)*delta_x(N))
TI=Temp(N)
CALL DIFSEQ(TIME,AA,BB,TL,TF,TBAR)
Temp(N)=TF
ENDIF

***** *** VARIABLE VOLUME TECHNIQUE ****************************************
IF(STORMODE.EQ.1.AND.TIN+1.GE.TEMP(1)) THEN !Charging, Temp in must be hotter than top node, otherwise no go
    IF(STORMODE.EQ.1) THEN
        I=N
        L=0
        TOTAL=0
        * !INCOMING CHARGING FLOW EXCEEDS TOTAL MASS IN TANK
        50 IF(I.EQ.0) THEN
            N=1
            TEMP(1)=TIN
            SEGMASS(1)=AREA*HTOTAL*DENSITYIN
        ENDIF
    ENDIF

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TOTAL=TOTAL+SEGMASS(I)
X=TOTAL-MASSIN
I=I-1
L=L+1 !THIS IS HERE SO THAT IT DOES DO LOOP (60)
WHEN ALL SEGMENTS ARE EXHAUSTED
EXCEPT FOR TOP
IF(X.LT.0) GOTO 50
SUM=0
IF(L.NE.1) THEN
   DO 60 J=0,L-2,1
      SUM=SUM+SEGMASS(N-J)*CP(N-J)*TEMP(N-J)
   CONTINUE
ELSE
   SUM=0
ENDIF
CPOUT=CP(N)
65 CPOLD=CPOUT
TOUT=(SUM+ABS(SEGMASS(I+1)-
   X)*CP(I+1)*TEMP(I+1))/(MASSIN*CPOUT)
CPOUT=1.500044+0.00276912*(TOUT-273.15)-1.3e-7*(TOUT-
   273.15)**2 !Temp has to be in C (from Type 151)
IF(ABS(CPOUT-CPOUT).GE.EPS)GOTO 65
SEGMASS(I+1)=X
N=I+2 !segments in tank now
C
Resetting mass array to new segments
IF(N.GE.2) THEN !When N is greater than 1
   SEGMASS(N)=SEGMASS(I+1)
   TEMP(N)=TEMP(I+1)
   DO 70 J=1,N-2,1
      SEGMASS(N-J)=SEGMASS(I+1-J)
      TEMP(N-J)=TEMP(I+1-J)
   CONTINUE
ELSE !When N=1
   SEGMASS(2)=SEGMASS(1)
   TEMP(2)=TEMP(1)
ENDIF
SEGMASS(1)=MASSIN
TEMP(1)=TIN
ELSEIF(Stormode.EQ.3) THEN !Discharging
   I=1
   TOTAL=0
75 TOTAL=TOTAL+SEGMASS(I)
X=TOTAL-MASSIN
I=I+1
IF(X.LT.0) GOTO 75
SUM=0
IF(I.GT.2)THEN
   DO 80 J=1,I-2,1
      SUM=SUM+SEGMASS(J)*CP(J)*TEMP(J)
   80 CONTINUE
ELSE
   SUM=0
ENDIF
CPOUT=CP(1)
CPOLD=CPOUT
TOUT=(SUM+ABS(SEGMASS(I-1)-X)*CP(I-1)*TEMP(I-1))/(MASSIN*CPOUT)
CPOUT=1.500044+0.00276912*(TOUT-273.15)-1.3e-7*(TOUT-273.15)**2 !Temp has to be in C (from Type 151)
IF(ABS(CPOUT-CPOUT).GE.EPS) GOTO 85
SEGMASS(I-1)=X
!segments in tank now
IF(I.EQ.2) THEN !discharge took place using only 1 segment
   N=N+1
ELSE
   N=N-(I-1)+2 !discharge took place using more than 1 segm.
ENDIF
C Resetting mass array to new segments
IF(N.GE.2.AND.I.GT.2)THEN !When N is greater than 1
   SEGMASS(1)=SEGMASS(I+1)
   TEMP(1)=TEMP(I+1)
   DO 90 j=1,N-1,1
      SEGMASS(j)=SEGMASS(I-2+j)
      TEMP(j)=TEMP(I-2+j)
   90 CONTINUE
ENDIF
SEGMASS(N)=MASSIN
TEMP(N)=TIN
ENDIF

THERMODYNAMIC PROPERTIES
98 DO 100 i=1,N
   E(i)=SegMass(i)*Cp(i)*(Temp(i)-Tdel)
   IF (E(i).LT.0) E(i)=0
   S(i)=Tref*SegMass(i)*Cp(i)*LOG(Temp(i)/Tdel)
   IF (S(i).LT.0) S(i)=0
   A(i)=E(i)-S(i)
100 CONTINUE

* Total Tank Summations
Energy3=0
Entropy3=0
Exergy3=0
DO 110 i=1,N
   Energy3=Energy3+E(i)
   Entropy3=Entropy3+S(i)
   Exergy3=Exergy3+A(i)
110 CONTINUE
* PERFORMANCE PARAMETER
   Perf3=0
   IF (Energy3.NE.0) Perf3=Exergy3/Energy3
*
   AVERAGE TANK TEMPERATURE
   Counter=0
   Totalmass=0
   DO 125 i=1,N
      Counter=Counter+Segmass(i)*Temp(i)
      Totalmass=Totalmass+Segmass(i)
   125 CONTINUE
   Avetemp=Counter/Totalmass-273.15
   130 PerStratOut(1)=Energy3
   PerStratOut(2)=Entropy3
   PerStratOut(3)=Exergy3
   PerStratOut(4)=Perf3
   PerStratOut(5)=Avetemp

RETURN
END
REFERENCES


14 Blair, Nathan. Email regarding SEGS VI model. October 2003.


VITA

Graduate College
University of Nevada, Las Vegas

Jade Gaal

Local Address:
429 Cannes Street
Henderson, NV 89015

Home Address:
4750 Lincoln Blvd Apt 392
Marina Del Rey, CA 90292

Degrees:
Bachelor of Science, Mechanical Engineering, 2001
University of Nevada, Las Vegas

Special Honors and Awards:
Engineer Intern, Spring 2001
Order of the Engineer, 2003
Tau Beta Pi Correspondence Secretary, 2001

Publications:

Thesis Title: A Comparison of Thermal Storage Models with a Solar Electric Generating System using TRNSYS

Thesis Examination Committee:
Chairperson, Dr. Robert F. Boehm, Ph.D.
Committee Member, Dr. Samir Moujaes, Ph.D.
Committee Member, Dr. Bingmei Fu, Ph.D.
Graduate Faculty Prespresentative, Dr. Jacimaria Batista, Ph.D.