Second law analysis of the transient behavior of solid media thermal storage utilizing finite difference computational modeling

Jason Scott Mulvey

University of Nevada, Las Vegas

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SECOND LAW ANALYSIS OF THE TRANSIENT BEHAVIOR OF SOLID MEDIA
THERMAL STORAGE UTILIZING FINITE DIFFERENCE COMPUTATIONAL
MODELING

by

Jason Mulvey

Bachelor of Science
University of Nevada, Las Vegas
1999

A thesis submitted in partial fulfillment
of the requirements for the

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

Graduate College
University of Nevada, Las Vegas
May 2003
The Thesis prepared by

Jason Mulvey

Entitled

Second Law Analysis of the Transient Behavior of Solid Media Thermal Storage Utilizing Finite Difference Computational Modeling

is approved in partial fulfillment of the requirements for the degree of

Master of Science in Mechanical Engineering

Examination Committee Member

William C. Kilby

Examination Committee Member

Graduate College Faculty Representative

Exam Committee Chair

Dean of the Graduate College

April 17, 2003
ABSTRACT

Second Law Analysis of the Transient Behavior of Solid Media Thermal Storage Utilizing Finite Difference Computational Modeling

by

Jason Mulvey

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

A computational model utilizing the finite difference method was developed to simulate the behavior of a simple storage system. The system analyzed utilizes the deposition of heat from a fluid to a solid matrix in the initial part of cycle followed by heat removal in the latter part. The storage system was divided into perpendicular slices with respect to the direction of the heat transfer fluid (HTF) flow. The symmetry of the design was then used to further reduce the area of the slice on which the calculations were performed. Two dimensional conduction and convection calculations were performed within the plane generated by each slice. Interaction between the slices was limited to only the HTF flowrate. It was assumed that the system would experience no losses to the ambient and the HTF contained in each slice would be fully mixed. First and Second Law analysis were incorporated as a means of evaluating different configurations of the storage system design.
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CHAPTER 1

INTRODUCTION

Description of Storage Need

The existing design of parabolic trough solar power plants contains two distinct disadvantages when compared to conventional power plants. The first disadvantage of the parabolic trough plants is that the hours of operation for the solar plant are limited by the hours of available sunlight. The second disadvantage experienced by parabolic solar power plants is the sporadic availability of sunlight during normal hours of operation that can occur during days of cloudiness.

One solution to these disadvantages is to utilize a backup energy source, such as a natural gas fired boiler. While this solution is successful in meeting the energy requirements of the plant, it does so at a cost. The natural gas must be purchased and its use is limited by regulations that govern renewable energy power plants. An alternative solution is the implementation of an energy storage system into the overall solar plant design.

During times of available solar energy, the storage system can be charged. When the plant experiences periods of solar energy deficits, the storage system can be discharged to supply the plant with the needed energy. The storage system can also be discharged in the evening after the sun has set. This allows the plant to extend its hours of operation beyond those dictated by the availability of the sun. The utilization of a
storage system and the charging-discharging scheme allows the plant to rely only on the renewable energy of the sun while still being competitive with conventional power plants as discussed by Pilkington Solar International [1].

Storage Implementation

The overall parabolic trough solar power plant can be divided into the three following subdivision of components: energy collection components, energy exchange components, and power production components. Refer to Figure 1 for an example of a typical plant layout.

![Figure 1 Typical Plant Layout](image-url)
The addition of a storage system would add a fourth subdivision to the plant design. The storage system would interact solely with the energy collection components. The remaining plant components would remain unchanged. Refer to Figure 2 for an example of a plant layout with storage added.

![Figure 2: Typical Plant Layout with Storage added](image)

The storage system would be connected to the existing plant’s components between the energy collection components and the energy exchange components. During times of normal operation, the flow of the heat transfer fluid (HTF) would leave the collector field and pass directly to the heat exchangers. During times of abundant solar energy, the HTF flow can be diverted through the storage system. This allows the storage system to be charged. During times of solar energy deficits or no sun conditions,
the flow of the HTF exiting the heat exchangers can be diverted through the storage system. This allows the storage system to be discharged and the plant to operate as if under normal solar energy conditions. The exact nature of the charging-discharging regime can be tailored to the specific plant’s needs.

Goals of Storage

A storage system can be utilized to achieve two distinct goals of power production. The first goal is to counteract sporadic declines in solar availability as experienced during periods of cloudiness. During periods of abundant solar energy, the heat transfer fluid can be passed through the storage system, thus allowing the system to be charged. When the plant experiences a decline in solar availability, the heat transfer fluid can again be passed through the storage system to discharge the stored energy. The energy removed from the storage system provides the power plant with the missing energy caused by the intermittent decline in solar availability and allows the power plant to maintain a constant level of power production. The responsiveness of the storage system and the ability to counteract intermittent declines in solar availability depend on the sizing of the storage system and the length of time the power plant experiences the decline.

The second goal is to extend the operation of the plant beyond the normal hours of solar availability. During periods of abundant solar energy, the heat transfer fluid is passed through the storage system. The excess energy is removed from the heat transfer fluid and stored in the storage system. As the sun sets, normal power production in the plant begins to decline due to the decrease in available solar energy. The heat transfer
fluid can be passed through the charged storage system in a discharge cycle. The previously stored energy is transferred into the heat transfer fluid and the power plant can maintain normal operating conditions. The sizing of the storage system and the amount of energy stored within determine the amount of time the normal operation conditions can be extended.

The two stated goals of storage could be achieved either separately or concurrently. The needs of the individual plant determine which of the goals are to be used in the storage design.

Evaluation of Storage

The design of the storage system contains many variables, which can result in different storage systems that meet the requirements of the power plant. Each of these designs is valid; however, one design may prove optimal. The definition of optimal depends on the application needs of the storage system. The storage systems being evaluated in this paper are all designed to take energy from the heat transfer fluid during the charging phase, store the energy in a solid state medium, then upon discharge transfer the stored energy back to the heat transfer fluid. Under ideal conditions, the total amount of energy stored in the storage system would be transferred back into the heat transfer fluid. In real world conditions, a complete transfer of energy between the storage media and the heat transfer fluid is impossible. Therefore, the amount of energy transferred from the storage system media to the heat transfer fluid will be used as a performance evaluator and determine which design is optimal.

Each storage system will be evaluated using the First and Second Laws of Thermodynamics. During a simulation, the total amount of energy transferred into the
storage system during the charging phase will be recorded. During the discharging phase, the total amount of energy transferred from the storage system will be recorded. The amount of energy removed from the storage system divided by the energy originally stored in the storage system will provide the First Law efficiency of the storage system. The different storage designs will be rated according to this performance indicator.

While energy transfer will occur between the heat transfer fluid and the storage system media as long as there exists a temperature difference, the quality of the energy being transferred is not considered. A Second Law evaluation will be performed to determine the change in availability of the HTF for each storage system. The different storage designs will then be rated according to this Second Law performance indicator. The results of the First and Second Law evaluations will be compared to see if the Second Law provides a better source for performance evaluations.

Literature Search

A literature search was performed to determine if there existed any information relative to the modeling of solid media thermal storage. Several sources mentioned information related to the focus of this paper. Pilkington Solar International [2] briefly discusses the possibility of solid media thermal storage, but provides only a theoretical approach. Rosen [3-5] and Razani [6] discuss sensible thermal storage and Second Law analysis; however, their focus was on a liquid storage media. Krane [7] provides the most related information in his investigation of the optimization of a distributed storage element. The approach uses a distributed storage element; however, the physical properties are assumed constant. Geyer’s [8] presentation to the 5th Framework Program
of the European Union illustrates a trend in solid media thermal storage, where actual
testing is done without first the use of complex computer simulations.

From the literature search, it was determined that there existed a need for a computer simulation that provided the user with the ability to vary the physical properties, flowrates, and temperatures with time, while still performing First and Second Law analysis on the modeled system. The program focused on in this paper is the result.
CHAPTER 2

PROPOSED STORAGE SYSTEM

Physical Dimensions and Layout

The concept of a storage system for parabolic trough solar power plants lends itself to various design options. The investigated system is a simple storage system utilizing a solid-state storage medium. The system consists of a volume of solid media with rectangular cross sections. The physical dimensions of the volume will be referred to as height, width, and depth. Width and depth will represent the horizontal dimensions of the volume, while height represents the vertical dimension. Refer to Figure 3 for an illustration of the storage volume.

A uniform system of piping is laid within the volume of concrete such that fluid flowing through the pipes maintains a horizontal orientation and transverses the volume along the axis created by the depth dimension. The pipe wall thickness and surface roughness are user defined and remain uniform for the entire piping array. Refer to Figure 3 for an illustration of the storage volume with piping. The benefit of this design is its modular nature. The design can easily be resized to match any energy storage requirement.
Figure 3  Storage Volume with Piping System and Dimensions Overlaid
CHAPTER 3

DEVELOPMENT OF FINITE DIFFERENCE MODEL

Input of Physical System into Model

The physical storage system is entered into the simulation program through user-required inputs. The user provides the program with the following storage system information:

- Length of storage system
- Width of storage system
- Height of storage system
- Number of pipes used in the storage system piping array
- Inner Diameter of the pipes used
- Outer Diameter of the pipes used

Once the physical system dimensions have been entered into the simulation program, the user then inputs the physical properties for the storage media, the piping, and the heat transfer fluid.

The required physical properties are the specific heat capacity and the density. For the solid media, the thermal conductivity is also required. The specific heat capacity and density are both assumed to be curve fit to a polynomial of no more than third order. The user needs only enter the coefficients required to match the polynomial used to fit the
physical properties of each material. Refer to Appendix page 44 for an example of the User Input file.

The simulation program checks the user-inputted data to verify that the described system is realistic in its physical sizing. Should one or more of the dimensions be incorrect for a realistic system, the program terminates and prompts the user with suggestions on fixing the problem. Refer to Appendix page 47 for an example of the program's realistic dimensions check subroutine.

After the user defined system has been verified for realistic dimensions, the user inputs the desired nodal system parameters. The program takes the realistic entered dimensions and utilizes symmetry to minimize the physical portion of the storage system that will be modeled. Refer to Appendix page 63 for illustrations of symmetric divisions. The program takes the user specified nodes in the X, Y, and Z directions and using the dimensions of the symmetrically divided section of storage, determines the spacing between each node. Figure 4 shows the symmetrically divided section of storage with the nodal system overlaid.

![Symmetrically Divided Subsection with the Nodal Overlay](image_url)

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Stability Criteria

The finite difference equations utilized by the program are explicit. The nodal spacing is calculated from the physical dimensions of the storage system and the number of nodes desired by the user. These facts combined make the use of a stability criterion necessary. Since the program reduces the physical system into a series of two-dimensional nodal arrays, the stability criterion, Eqn. (1), will be used to determine the proper simulation time step.

\[
\Delta t \leq \frac{3C_p \rho}{2h \left( \frac{1}{\Delta Y} + \frac{1}{\Delta X} \right) + 8k \left( \frac{1}{\Delta Y^2} + \frac{1}{\Delta X^2} \right)}
\]  

(1)

The simulation allows the user to input new heat transfer fluid temperatures and flowrates at user defined time intervals. The calculated simulation time step may not equal the user defined time intervals. If this situation occurs, the program adjusts its outputs to simulate the fractional time step that is experienced in order to maintain constant user defined time intervals. This ensures that the user defined inputs of heat transfer fluid temperatures and flowrates are entered during the proper time and the stability of the finite difference equations is maintained. Refer to Appendix page 49 for the subroutine used by the program to allow for fractional time steps.
Finite Difference Calculations

The Finite Difference calculations used in the simulation are explicit in nature. The development of the nodal system yields four distinct node types:

1. Interior Nodes
2. Edge Nodes
3. Corner Nodes
4. Interface Nodes

\[
\sum q_i = \rho C_p Vol_{(x,y,z)} \frac{T^{i+\Delta t}_{(x,y,z)} - T^i_{(x,y,z)}}{\Delta t}
\]  \hspace{1cm} (2)

Refer to Figure 5 for an illustration of the nodal structure. Each type of node requires an appropriate form of the heat equation. Starting from the basic heat equation, Eqn. (2) [9], it can be shown that examples of the appropriate equations for each type of node are as follows:

Interior Nodes:

\[
T^{i+\Delta t}_{(x,y,z)} = T^i_{(x,y,z)} + \alpha \Delta t \left( \frac{T^i_{(x+1,y,z)} + T^i_{(x-1,y,z)} - 2T^i_{(x,y,z)}}{\Delta x^2} \right) + \frac{T^i_{(x,y+1,z)} + T^i_{(x,y-1,z)} - 2T^i_{(x,y,z)}}{\Delta y^2}
\]  \hspace{1cm} (3)

Edge Nodes:
Corner Nodes:

\[
T^{i+\Delta t}_{(x, y, z)} = T^i_{(x, y, z)} + \alpha \Delta t \left( \frac{T^i_{(x+1, y, z)} + T^i_{(x-1, y, z)} - 2T^i_{(x, y, z)}}{\Delta Y^2} + \frac{2T^i_{(x, y-1, z)} - 2T^i_{(x, y, z)}}{\Delta Y^2} \right)
\]

Interface Nodes:

\[
\alpha \left( \frac{\Delta X}{\Delta Y} \left( T^i_{(x+1, y, z)} + T^i_{(x-1, y, z)} - 2T^i_{(x, y, z)} \right) + \frac{\Delta Y}{\Delta X} \left( T^i_{(x, y+1, z)} + T^i_{(x, y-1, z)} - 2T^i_{(x, y, z)} \right) \right) + \frac{h_{\text{Area}}_{\text{conv}}}{\rho C_p} \left( T^i_{HF} - T^i_{(x, y, z)} \right)
\]

\[
T^{i+\Delta t}_{(x, y, z)} = T^i_{(x, y, z)} + \Delta t \frac{\rho C_p}{\text{Vol}(x, y, z)} \left( T^i_{HF} - T^i_{(x, y, z)} \right)
\]
Figure 5 illustrates the various types of nodes and their location within the Z-axis slice. The maximum number of nodes a single node has interaction with is four, as in the case of the interior nodes. The minimum number of nodes a single node has interaction with is two, as in the case of the corner nodes. All nodes contain conduction terms in their specific forms of the heat equation. Only the interface nodes contain additional
convection terms in their specific forms heat equations. The program uses the user defined nodal array to determine which form of the heat equation to use with each node. Refer to page 46 for the program’s routine. For the interface nodes, the program calculates the convective heat transfer coefficient through the use of Eqns. (7-12). A convective heat transfer coefficient is calculated for every Z-direction slice during every time step increment.

\[
U_{\text{mean}} = \frac{V}{\pi \left(\frac{D_i}{2}\right)^2}
\]  
\hspace{2cm} (7)

\[
\text{Pr} = \frac{\mu c_p}{k}
\]  
\hspace{2cm} (8)

\[
\text{Re} = \frac{\rho U_{\text{mean}} D_i}{\mu}
\]  
\hspace{2cm} (9)

\[
\xi = \frac{1}{(0.790 \ln(\text{Re}) - 1.64)^2}
\]  
\hspace{2cm} (10)

\[
\text{Nu} = \frac{\xi (\text{Re} - 1000) \text{Pr}}{1.07 + 12.7 \sqrt{\frac{\xi}{8} \left(\text{Pr}^{1/3} - 1\right)}}
\]  
\hspace{2cm} (11)

\[
h = \frac{\text{Nu} \cdot k}{D_i}
\]  
\hspace{2cm} (12)

**Z-Direction Slice Interaction**

The program assumes that the only interaction in the Z-direction is through the flow of the HTF between Z-direction slices. This interaction between the slices is
calculated using Eqn. (13) and determines the temperature effect associated with this interaction.

\[
T_{HTF_2}^{i+\Delta t} = + \Delta E_{storage-interaction} \left( \frac{Vol_Z \cdot C_{pl} \cdot \rho_Z}{Vol_Z \cdot C_{pl} \cdot \rho_Z} \right)
\]  

(13)

Efficiencies

The First and Second Law efficiencies are used as evaluation tools in rating and comparing various storage design options. The First Law efficiency calculation is based on the amount of energy stored and removed from the storage system over a given time interval. The First Law efficiency is calculated using Eqn. (14). The Second Law efficiency calculation is based on the quality of the energy transferred between the HTF and the storage system. Unlike the First Law Efficiency calculation, the Second Law efficiency calculation involves not only the storage system, but the HTF flowing through it. Equation (15) is used to calculate the Second Law efficiency.

\[
1^{st} \text{ Law efficiency} = \frac{\text{Energy removed}}{\text{Energy stored}} \\
2^{nd} \text{ Law efficiency} = \frac{\Delta HTF Availability_{Discharging}}{\Delta HTF Availability_{Charging}}
\]  

(14)  

(15)
The First Law efficiency determines how much energy was successfully stored and then removed from the storage system. It does not take into account where the energy goes, only that it has left the storage system. The Second Law efficiency determines how much of the energy transferred between the storage system and the HTF is actually useful for the production of power.
CHAPTER 4

MODELED STORAGE SYSTEMS

Description of Systems

Eight unique storage systems were developed for use with the simulation
program. Each system was described through the use of twenty-one variables. Refer to
Appendix page 44 for an example of the user-defined variables. The variables used to
describe the fluid properties, the piping properties, and the nodal arrays were constant
and identical for each of the eight storage systems. For the fluid properties, the HTF
Therminal VP1 was chosen. Only the variables used to describe the solid media portion
of the storage system were allowed to be varied within the eight storage systems
modeled. These six variables are:

1. Length
2. Width
3. Depth
4. Specific Heat Capacity
5. Density
6. Thermal Conductivity

Refer to Table 1 for the eight systems’ solid media variables. The Depth variable was
kept constant for each of the eight systems. This was done to remove the influence
piping length may have on the calculated results and to keep the associated pumping
requirements the same for each system. The Density variable was kept constant to
decrease the number of modeled systems to a reasonable number.

TABLE 1 – Modeled Systems’ Variable Values

<table>
<thead>
<tr>
<th>System</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (m)</td>
<td>15.0</td>
<td>10.6</td>
<td>15.0</td>
<td>10.6</td>
<td>15.0</td>
<td>10.6</td>
<td>15.0</td>
<td>10.6</td>
</tr>
<tr>
<td>Width (m)</td>
<td>15.0</td>
<td>10.6</td>
<td>15.0</td>
<td>10.6</td>
<td>15.0</td>
<td>10.6</td>
<td>15.0</td>
<td>10.6</td>
</tr>
<tr>
<td>Depth (m)</td>
<td>10.0</td>
<td>10.0</td>
<td>10.0</td>
<td>10.0</td>
<td>10.0</td>
<td>10.0</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Cp (kJ/ kg K)</td>
<td>0.627</td>
<td>1.254</td>
<td>1.254</td>
<td>0.627</td>
<td>0.627</td>
<td>1.254</td>
<td>1.254</td>
<td>0.627</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>2360.0</td>
<td>2360.0</td>
<td>2360.0</td>
<td>2360.0</td>
<td>2360.0</td>
<td>2360.0</td>
<td>2360.0</td>
<td>2360.0</td>
</tr>
<tr>
<td>Thermal Conductivity (W/ m K)</td>
<td>1.6</td>
<td>1.6</td>
<td>1.6</td>
<td>1.6</td>
<td>3.2</td>
<td>3.2</td>
<td>3.2</td>
<td>3.2</td>
</tr>
</tbody>
</table>
CHAPTER 5

RESULTS

Two different simulations were run for each of the eight models. The first simulation was a 24-hour simulation with the defined flowrate and temperature profiles shown in Fig 6. The second simulation was a 168-hour simulation. Repeating the profiles from the first simulation 7 times as shown in Fig 7 created the flowrate and temperature profiles for the second simulation.

Figure 6 24 Hour Simulation Flowrate and Temperature Profiles
Once the simulations were completed, the First Law and Second Law efficiencies were calculated for the 1-Day and 1-Week simulations of the eight models. Table 2 summarizes the calculated First Law efficiencies. Table 3 summarizes the calculated Second Law efficiencies. The First Law efficiencies were all near 100%. This was to be expected, due to the assumptions made. The First Law efficiencies illustrate that nearly all the energy stored in the system is removed during the discharge phase. The Second Law efficiencies are much lower than the corresponding First Law efficiencies. This means that although nearly 100% of the energy is being removed from the storage system
during the discharge phase, the actual useful energy being transferred to the HTF is much less.

**TABLE 2 – First Law Efficiencies**

<table>
<thead>
<tr>
<th>System</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-Day</td>
<td>99.22%</td>
<td>96.48%</td>
<td>99.61%</td>
<td>98.43%</td>
<td>98.43%</td>
<td>96.17%</td>
<td>99.22%</td>
<td>96.81%</td>
</tr>
<tr>
<td>1-Week</td>
<td>99.89%</td>
<td>99.69%</td>
<td>99.94%</td>
<td>99.77%</td>
<td>99.77%</td>
<td>99.62%</td>
<td>99.89%</td>
<td>99.53%</td>
</tr>
</tbody>
</table>

**TABLE 3 – Second Law Efficiencies**

<table>
<thead>
<tr>
<th>System</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-Day</td>
<td>77.65%</td>
<td>85.98%</td>
<td>86.21%</td>
<td>75.55%</td>
<td>66.38%</td>
<td>79.98%</td>
<td>79.52%</td>
<td>62.62%</td>
</tr>
<tr>
<td>1-Week</td>
<td>78.36%</td>
<td>86.98%</td>
<td>86.21%</td>
<td>75.55%</td>
<td>67.38%</td>
<td>81.31%</td>
<td>79.53%</td>
<td>62.72%</td>
</tr>
</tbody>
</table>

After the efficiency calculations were made, six different comparisons were performed on the eight models. It should be noted that for the graphs associated with the six comparisons, the displayed time increment is one hour. A smaller time increment would yield smoother graph lines and show slight variations between the compared systems that the larger time increment is unable to. The six different comparisons were:

1. Varied properties, identical energy capacity
2. Identical properties except thermal conductivity
3. Identical properties except specific heat capacity
4. Identical volume dimensions
5. Identical specific heat capacities
6. Identical thermal conductivities
The comparison of systems with different design specifications, but similar energy storage capacities best illustrates the design choices most often faced by an engineer. For this comparison, systems 1 and 2 were compared. Each of these systems has the ability to hold the equal amounts of energy at a given storage media temperature. Figure 8 illustrates the associative energy levels for the two storage systems during the course of simulation 1. They are nearly identical. From this energy analysis of the storage system, it would be impossible to determine which of the systems would be the better design choice. By viewing the systems’ interactions with the HTF from the HTF changes, instead of the storage media changes, a distinct difference between the two systems arises. The change in the availability of the HTF passing through each storage system is plotted in FIG 8. It is shown that the HTF passing through system 2 experiences a greater change in availability than the HTF passing through system 1 under identical flowrate and temperature profiles.
The first comparison illustrates how performing just an energy analysis on the storage system may not provide the engineer with all the information necessary for making a design choice. The addition of an analysis on the change in availability of the HTF provides the designer with more information from which to base the design decision on. The remaining five comparisons investigate the influence of various storage system properties on the calculated change in availability of the HTF and the change in energy of the storage system.
The second comparison groups the eight models into pairs. Each pair of models has identical storage properties except for the thermal conductivity of the storage media. The pair groups are as follows:

1. Model 1 and Model 5
2. Model 2 and Model 6
3. Model 3 and Model 7
4. Model 4 and Model 8

Figures 9 through 12 show the comparisons of the change in energy of the storage system and change in availability of the HTF for each model pairing. In each pairing, it is shown that the changes in energy of the storage systems are identical. The change in the energy of the storage system is not influenced by the thermal conductivity of the storage media. The differences in thermal conductivity do influence the calculated change in availability of the HTF. The model in each pairing that has the greater thermal conductivity value also has the greater change in availability of the HTF. This implies that when given two identical systems with only a variance in the thermal conductivity, the system with the greater thermal conductivity value should be considered for the design choice.
Figure 9  Identical properties except thermal conductivity, Models 1 and 5
Varying k - System 2 and 6

![Graph showing change in available energy and energy over time for two systems.](image)

Figure 10 Identical properties except thermal conductivity, Models 2 and 6
Figure 11 Identical properties except thermal conductivity, Models 3 and 7
As in the second comparison, the third comparison groups the eight models into pairs. Each pair of models has identical storage properties except for the specific heat capacity of the storage media. The pair groups are as follows:

1. Model 1 and Model 3  
2. Model 2 and Model 4  
3. Model 5 and Model 7  
4. Model 6 and Model 8

Figures 13 through 16 show the comparisons of the change in energy of the storage system and change in availability of the HTF for each model pairing. In each pairing, the

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model with the greater specific heat capacity had a greater associated change in energy of
the storage media. This can be attributed to the greater specific heat capacity allowing
the storage media to hold more energy at a given temperature. The change in availability
of the HTF was also effected by the differences in the specific heat capacities of the
models. In each pairing, the model with the lower specific heat capacity experienced a
greater change in the availability of the HTF. From an energy analysis, with all things
identical except the specific heat capacity of the storage media, the system with the larger
specific heat capacity would appear to be the better design choice. Since the ultimate
goal of a storage system is to change the associated temperature of the HTF, this result
can be misleading. The analysis of the change in availability of the HTF shows that the
system with the smaller specific heat capacity provides the greater change in the
availability of the HTF and thus is actually the preferred design choice.
Figure 13  Identical properties except specific heat capacity, Models 1 and 3
Figure 14  Identical properties except specific heat capacity, Models 2 and 4
Figure 15 Identical properties except specific heat capacity, Models 5 and 7
Figure 16  Identical properties except specific heat capacity, Models 6 and 8

The remaining three comparisons investigate how dominant of a role a single property can have on a storage design. The fourth comparison looks at the role the physical dimensions of the storage system have on its overall evaluation. The eight models were divided into the following two groups:

1. Models 1, 3, 5, and 7
2. Models 2, 4, 6, and 8

Figures 17 and 18 show the respective comparisons of these two groupings. In each grouping, the only constant between all the models was the physical dimensions of the
storage system. In each of the groupings, no trend could be established based on holding the physical dimensions of the storage systems constant.

Figure 17  Identical volume dimensions, Models 1, 3, 5, and 7
The fifth comparison looks at the role the specific heat capacity of the storage medium has on the system’s overall evaluation. The eight models were divided into the following two groups:

1. Models 1, 4, 5, and 8
2. Models 2, 3, 6, and 7

Figures 19 and 20 show the respective comparisons of these two groupings. In each grouping, the only constant between all the models was the specific heat capacity of the storage medium. In each of the groupings, no trend could be established based on holding the specific heat capacity of the storage medium constant.
Figure 19  Identical specific heat capacities, Models 1, 4, 5, and 8
Figure 20 Identical specific heat capacities, Models 2, 3, 6, and 7

The sixth and final comparison looks at the role the thermal conductivity of the storage medium has on the system's overall evaluation. The eight models were divided into the following two groups:

1. Models 1, 2, 3, and 4
2. Models 5, 6, 7, and 8

Figures 21 and 22 show the respective comparisons of these two groupings. In each grouping, the only constant between all the models was the thermal conductivity of the storage medium.
storage medium. In each of the groupings, no trend could be established based on holding the thermal conductivity of the storage medium constant.

Comparisons four through six illustrate an important idea in storage system design. While a single property may influence the performance of a given system, no one property investigated dominates the system evaluation to the point of becoming the sole focus of the designer.

Figure 21 Identical thermal heat conductivities, Models 1, 2, 3, and 4
Figure 22 Identical thermal heat conductivities, Models 5, 6, 7, and 8
CONCLUSIONS

The program developed for the modeling of solid media thermal storage systems was successful. The nature of the user defined inputs and parameters allows for reasonably timed simulations of various system configurations. The user is able to generate simulations ranging from as little as one hour, to as long as desired. The program provides the user with a first law performance analysis as well as a second law performance analysis. The combination of both types of analysis provides the user with information from both the storage and HTF perspectives. One cannot conclude from these simulations, which of the two analyses is better for performance evaluations. Instead, it is recommended that both analyses be used in conjunction with one another to form a more complete understanding of the designed system.

The eight models used in the testing of the simulation program demonstrate the validity of solid media thermal storage from a performance standpoint. Further comparative testing and cost analysis would be needed to determine if solid media thermal storage is a viable consideration over other forms of thermal storage.
## USER INPUT FILE – EXAMPLE

<table>
<thead>
<tr>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.10</td>
<td>* Pipe Inner Diameter (m)</td>
</tr>
<tr>
<td>0.12</td>
<td>* Pipe Outer Diameter (m)</td>
</tr>
<tr>
<td>75</td>
<td>* Number of Pipes in the Horizontal Direction</td>
</tr>
<tr>
<td>75</td>
<td>* Number of Pipes in the Vertical Direction</td>
</tr>
<tr>
<td>2</td>
<td>* Pipe Spacing in the Horizontal Direction (m)</td>
</tr>
<tr>
<td>2</td>
<td>* Pipe Spacing in the Vertical Direction (m)</td>
</tr>
<tr>
<td>15.0</td>
<td>* Length of Storage Volume (m)</td>
</tr>
<tr>
<td>15.0</td>
<td>* Width of Storage Volume (m)</td>
</tr>
<tr>
<td>10.0</td>
<td>* Depth of Storage Volume (m)</td>
</tr>
<tr>
<td>0.2517</td>
<td>* Fluid Cp polynomial constant 1</td>
</tr>
<tr>
<td>0.0061</td>
<td>* Fluid Cp polynomial constant 2</td>
</tr>
<tr>
<td>-0.000007</td>
<td>* Fluid Cp polynomial constant 3</td>
</tr>
<tr>
<td>0.00000005</td>
<td>* Fluid Cp polynomial constant 4</td>
</tr>
<tr>
<td>1407.6</td>
<td>* Fluid Density polynomial constant 1</td>
</tr>
<tr>
<td>-1.6578</td>
<td>* Fluid Density polynomial constant 2</td>
</tr>
<tr>
<td>0.0023</td>
<td>* Fluid Density polynomial constant 3</td>
</tr>
<tr>
<td>-0.000002</td>
<td>* Fluid Density polynomial constant 4</td>
</tr>
<tr>
<td>0.001</td>
<td>* Fluid Viscosity polynomial constant 1</td>
</tr>
<tr>
<td>0.0</td>
<td>* Fluid Viscosity polynomial constant 2</td>
</tr>
<tr>
<td>0.0</td>
<td>* Fluid Viscosity polynomial constant 3</td>
</tr>
<tr>
<td>0.0</td>
<td>* Fluid Viscosity polynomial constant 4</td>
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<tr>
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<tr>
<td>0.0</td>
<td>* Fluid Viscosity polynomial constant 6</td>
</tr>
<tr>
<td>0.0</td>
<td>* Fluid Viscosity polynomial constant 7</td>
</tr>
<tr>
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<td>* Fluid Thermal Conductivity polynomial constant 1</td>
</tr>
<tr>
<td>-0.0000004</td>
<td>* Fluid Thermal Conductivity polynomial constant 2</td>
</tr>
<tr>
<td>-0.0000002</td>
<td>* Fluid Thermal Conductivity polynomial constant 3</td>
</tr>
<tr>
<td>-0.000000000008</td>
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</tr>
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</tr>
<tr>
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</tr>
<tr>
<td>0</td>
<td>* Solid Cp polynomial constant 3</td>
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<tr>
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<td>2360</td>
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</tr>
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</tr>
<tr>
<td>0</td>
<td>* Solid Density polynomial constant 3</td>
</tr>
<tr>
<td>0</td>
<td>* Solid Density polynomial constant 4</td>
</tr>
<tr>
<td>1.6</td>
<td>* Solid Thermal Conductivity</td>
</tr>
<tr>
<td>0</td>
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</tr>
<tr>
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<tr>
<td>0</td>
<td>* Piping Density polynomial constant 3</td>
</tr>
<tr>
<td>0</td>
<td>* Piping Density polynomial constant 4</td>
</tr>
<tr>
<td>10</td>
<td>* Number of Nodes in the Horizontal Direction</td>
</tr>
<tr>
<td>10</td>
<td>* Number of Nodes in the Vertical Direction</td>
</tr>
<tr>
<td>10</td>
<td>* Number of Nodes in the Depth Direction</td>
</tr>
<tr>
<td>573.0</td>
<td>* Initial Temperature (K)</td>
</tr>
<tr>
<td>3600</td>
<td>* Simulation Timestep (s)</td>
</tr>
</tbody>
</table>
PROGRAM CODE

PROGRAM Thermal_Storage

**
* This is program Thermal Storage
* It allows for user defined fluid, solid, and pipe properties.
* It handles the convective and conduction equations as well as calculating
* the change in Availability (Exergy) for the fluid based on entrance and exit temps.
*
* Written By: Jason S. Mulvey
**

CHARACTER*24 STRING
REAL PipeDi, PipeDo
INTEGER PipeNumX, PipeNumY
REAL PipeSpaceX, PipeSpaceY
REAL Length, Width, Depth
REAL Fcp1, Fcp2, Fcp3, Fcp4
REAL Frho1, Frho2, Frho3, Frho4
REAL Scp1, Scp2, Scp3, Scp4
REAL Sk
REAL Srho1, Srho2, Srho3, Srho4
REAL Pcp1, Pcp2, Pcp3, Pcp4
REAL Prho1, Prho2, Prho3, Prho4
REAL InitialTemp
INTEGER NodeX, NodeY, NodeZ
REAL XSpace, YSpace, ZSpace
REAL TEMP(10,10,100,3)
INTEGER XX, YY, ZZ
REAL deltaT
REAL Vdot, FTempIn
REAL Timestep
INTEGER Iterations
REAL Remain
REAL TempAVG, cpalpha, rhoalpha, alpha
REAL cp1, rho1, cp2, rho2
REAL cpf, rhof, Volf, TEMPOUT, TEMPIN
REAL Availability
REAL DeltaEf, DeltaEs
REAL Ef(2), Es(2)
REAL Volmf, Volms
REAL H, FNu, Fk, FDensity, squiggle
INTEGER FLUIDNODEX, FLUIDNODEY

**
* Begin Reading Data File containing constants
**

OPEN (UNIT=1, FILE="CONSTANTS.DAT")
OPEN (UNIT=3, FILE="OUTPUTS.DAT")

CALL FDATE(STRING)
WRITE(*,*) "Program Started on:")
WRITE(*,*) STRING
WRITE(3,*) "Program Started on:")
WRITE(3,*) STRING

READ (1,*) PipeDi
READ (1,*) PipeDo
READ (1,*) PipeNumX
READ (1,*) PipeNumY
READ (1,*) PipeSpaceX
READ (1,*) PipeSpaceY
READ (1,*) Length
READ (1,*) Width
READ (1,*) Depth
READ (1,*) Fcpl
READ (1,*) Fcp2
READ (1,*) Fcp3
READ (1,*) Fcp4
READ (1,*) Frhol
READ (1,*) Frho2
READ (1,*) Frho3
READ (1,*) Frho4
READ (1,*) Fvis1
READ (1,*) Fvis2
READ (1,*) Fvis3
READ (1,*) Fvis4
READ (1,*) Fvis5
READ (1,*) Fvis6
READ (1,*) Fvis7
READ (1,*) Fk1
READ (1,*) Fk2
READ (1,*) Fk3
READ (1,*) Fk4
READ (1,*) Scpl
READ (1,*) Scp2
READ (1,*) Scp3
READ (1,*) Scp4
READ (1,*) Srhol
READ (1,*) Srho2
READ (1,*) Srho3
READ (1,*) Srho4
READ (1,*) Sk
READ (1,*) Pcp1
READ (1,*) Pcp2
READ (1,*) Pcp3
READ (1,*) Pcp4
READ (1,*) Prho1
READ (1,*) Prho2
READ (1,*) Prho3
READ (1,*) Prho4
READ (1,*) NodeX
READ (1,*) NodeY
READ (1,*) NodeZ
READ (1,*) InitialTemp
READ (1,*) Timestep

CLOSE (UNIT=1)

**
* Adjustment to PipeSpacing to ensure proper realistic fit. *
**
PipeSpaceX=(Width/PipeNumX-PipeDo)
PipeSpaceY=(Length/PipeNumY-PipeDo)

**
* Checks sizing of storage for realistic fit. *
**

IF((PipeNumX*PipeDo).GT.Width) THEN
WRITE(*,*) "ERROR. 
&Either decrease pipe diameter, decrease number of pipes in the 
&X-direction, or increase width."
GOTO 666
ENDIF

IF((PipeNumY*PipeDo).GT.Length) THEN
WRITE(*,*) "ERROR. 
&Either decrease pipe diameter, decrease number of pipes in the 
&Y-direction, or increase width."
ENDIF

**
* Determines 3D nodal spacing.
**
IF (NodeX.GT.1) THEN
XSpace=0.5*(PipeDo+PipeSpaceX)/(NodeX-1)
ELSE
XSpace=0.5*(PipeDo+PipeSpaceX)
ENDIF

IF (NodeY.GT.1) THEN
YSpace=0.5*(PipeDo+PipeSpaceY)/(NodeY-1)
ELSE
YSpace=0.5*(PipeDo+PipeSpaceY)
ENDIF

ZSpace=Depth/(NodeZ)
**
* Initialize Storage Array Temperature
**

DO 10 XX=1,NodeX
DO 11 YY=1,NodeY
DO 12 ZZ=1,NodeZ

TEMP(XX,YY,ZZ,1)=InitialTemp

12 CONTINUE
11 CONTINUE
10 CONTINUE
**
* Begin Calculations
**

OPEN (UNIT=2, FILE="Flow_Temp.DAT")
800 READ (2,*) Vdot
READ (2,*) FTempIn

*** This allows the user to terminate the run, though its not very elegant of a way.

IF ((Vdot.EQ.(0.0001)).AND.(FTempIn.EQ.(0.0001))) THEN
GOTO 665
ENDIF
IF (Vdot.LT.0) THEN
WRITE (*,*) "Error! Vdot is negative."
GOTO 665
ENDIF

Iterations=AIINT(4*Timestep*Vdot/
& (3.14*PipeDi*PipeDi*Zspace*PipeNumX*PipeNumY))+1

Remain=(4*Timestep*Vdot/
& (3.14*PipeDi*PipeDi*Zspace*PipeNumX*PipeNumY))
&-AIINT(4*Timestep*Vdot/
&(3.14*PipeDi*PipeDi*Zspace*PipeNumX*PipeNumY))

**
* Determination of whether or not a node is in the fluid or solid media
**

FluidNodeX=AIINT(PipeDo/(2*XSpace))
FluidNodeY=AIINT(PipeDo/(2*XSpace))

**
* Average Alpha calculation
**

TempAVG=0.0
Do 33 XX=1,NodeX
Do 34 YY=1,NodeY
Do 35 ZZ=1,NodeZ

IF((XX.GT.FluidNodeX).OR.(YY.GT.FluidNodeY))THEN
TempAVG=TempAVG/(NodeX*NodeY*NodeZ-
FluidNodeX*FluidNodeY*NodeZ)
ENDIF

35 CONTINUE
34 CONTINUE
33 CONTINUE

TempAVG=TempAVG/(NodeX*NodeY*NodeZ-
FluidNodeX*FluidNodeY*NodeZ)

cpalpha=Scp1+Scp2*TempAVG+Scp3*TempAVG*TempAVG+Scp4*TempAV
G
& *TempAVG*TempAVG

rhoalpha=Srhol+Srhol2*TempAVG+Srhol3*TempAVG*TempAVG+Srhol4*Tem
pAVG

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& *TempAVG*TempAVG

\[
\alpha = \frac{S_k}{(c_{p\alpha}\rho_{\alpha})}
\]

**
* Calculates the h value for entering HTF
* Assumes fully developed turbulent flow.
**

\[
F_{\text{density}} = F_{\rho_1} + F_{\rho_2} F_{\text{TEMP}} + F_{\rho_3} F_{\text{TEMP}}
\]
& *F_{\text{TEMP}} + F_{\rho_4} F_{\text{TEMP}}
& *F_{\text{TEMP}}

\[
F_{cp} = F_{cp_1} + F_{cp_2} F_{\text{TEMP}} + F_{cp_3} F_{\text{TEMP}}
\]
& +F_{cp_4} F_{\text{TEMP}}
& *F_{\text{TEMP}}

\[
F_{vis} = F_{vis_1} + F_{vis_2} F_{\text{TEMP}} + F_{vis_3} F_{\text{TEMP}}
\]
& +F_{vis_4} F_{\text{TEMP}}
& *F_{\text{TEMP}}
& +F_{vis_5} F_{\text{TEMP}}
& *F_{\text{TEMP}}
& +F_{vis_6} F_{\text{TEMP}}
& *F_{\text{TEMP}}
& +F_{vis_7} F_{\text{TEMP}}
& *F_{\text{TEMP}}
& *F_{\text{TEMP}}

\[
F_K = F_{k_1} + F_{k_2} F_{\text{TEMP}} + F_{k_3} F_{\text{TEMP}}
\]
& +F_{k_4} F_{\text{TEMP}}
& *F_{\text{TEMP}}

\[
F_{um} = \frac{V_{dot} 4}{(3.14 \times \text{PipeDi} \times \text{PipeDi} \times \text{PipeNumX} \times \text{PipeNumY})}
\]

\[
F_{Re} = F_{\text{density}} F_{um} \times \text{PipeDi}/F_{vis}
\]
IF (F_{Re} .LT. (2300.0)) THEN
F_{Re} = 2300.0
ENDIF

\[
F_{Pr} = F_{vis} F_{cp}/F_{k}
\]
squiggle = 1/((1.82*(LOG10(F_{Re}))-1.64)*(1.82*(LOG10(F_{Re}))-1.64))

\[
F_{Nu} = \frac{(\text{squiggle}/8)*(F_{Re}-1000)*F_{Pr}*(1+((\text{PipeDi}/ZSpace)**(2/3)))}{(1+12.7* (\text{SQRT(squiggle/8)}))*((F_{Pr}**(2/3))-1)}
\]
\[ h = \frac{F_{Nu} F_k}{\text{PipeDi}} \]

IF (V\text{dot}. EQ. (0.0)) THEN
\[ h = 0.0 \]
ENDIF

**
* Stability criteria check
**

IF ((Timestep/Iterations).LT.(3*cpalpha*rhoalpha/(2*h & *(1/YSpace+1/XSpace)+8*Sk*(1/(YSpace*YSpace) &+1/(XSpace*XSpace)))))) THEN

\[ \text{deltat} = \text{Timestep}/\text{Iterations} \]
ELSE
\[ \text{deltat} = 3*cpalpha*rhoalpha/(2*h*(1/YSpace+1/XSpace)+8 & *Sk*(1/(YSpace*YSpace)+1/(XSpace*XSpace))) \]
\[ \text{Iterations} = \text{AINT}((\text{Timestep}/\text{deltat})+1) \]
\[ \text{Remain} = (\text{Timestep}/\text{deltat})-\text{AINT}((\text{Timestep}/\text{deltat}) \]
ENDIF

**
* Determines the amount of Energy associated with the given temperatures for the fluid and solid
**

\[ \text{ES}(1) = 0.0 \]
\[ \text{EF}(1) = 0.0 \]
\[ \text{STempAVG1} = 0.0 \]
\[ \text{FTempAVG1} = 0.0 \]
Do 887 XX = 1, NodeX
Do 888 YY = 1, NodeY
Do 889 ZZ = 1, NodeZ

IF ((XX.GT.FluidNodeX).OR.(YY.GT.FluidNodeY)) THEN
\[ \text{STempAVG1} = \text{Temp}(XX,YY,ZZ,1)+\text{STempAVG1} \]
ELSE
\[ \text{FTempAVG1} = \text{Temp}(XX,YY,ZZ,1)+\text{FTempAVG1} \]
ENDIF
CONTINUE
CONTINUE
CONTINUE

STempAVG1 = STempAVG1 / (NodeX * NodeY * NodeZ - FluidNodeX & * FluidNodeY * NodeZ)

FTempAVG1 = FTempAVG1 / (FluidNodeX & * FluidNodeY * NodeZ)

cpSAvg1 = Scp1 + Scp2 * STempAVG1 + Scp3 * STempAVG1 * STempAVG1 & + Scp4 * STempAVG1 & * STempAVG1 * STempAVG1

cpFAvg1 = Fcp1 + Fcp2 * FTempAVG1 + Fcp3 * FTempAVG1 * FTempAVG1 & + Fcp4 * FTempAVG1 & * FTempAVG1 * FTempAVG1

rhoSAvg1 = Srho1 + Srho2 * STempAVG1 + Srho3 * STempAVG1 & * STempAVG1 + Srho4 * STempAVG1 & * STempAVG1 * STempAVG1

rhoFAvg1 = Frho1 + Frho2 * FTempAVG1 + Frho3 * FTempAVG1 & * FTempAVG1 + Frho4 * FTempAVG1 & * FTempAVG1 * FTempAVG1

ES(l) = cpSAvg1 * rhoSAvg1 * STempAVG1 * (Length - PipeDo/2) & * (Width - PipeDo/2) * Depth

EF(l) = cpFAvg1 * rhoFAvg1 * FTempAVG1 * (PipeDo/2) & * (PipeDo/2) * Depth * 3.14

**
* Start of Time based Iterative Loop
**

DO 77 TT = 1, Iterations
WRITE(*, *) TT, "****", Iterations

DO 5 ZZ = 1, NodeZ

**
* Calculates the h value for each Z node
*
* Assumes fully developed turbulent flow.
**

\[
\text{Fdensity} = F\rho_1 + F\rho_2 \cdot \text{TEMP}(1,1,ZZ,1) + F\rho_3 \cdot \text{TEMP}(1,1,ZZ,1) + F\rho_4 \cdot \text{TEMP}(1,1,ZZ,1) \\
& + F\rho_5 \cdot \text{TEMP}(1,1,ZZ,1) + F\rho_6 \cdot \text{TEMP}(1,1,ZZ,1)
\]

\[
\text{Fcp} = Fc_{p1} + Fc_{p2} \cdot \text{TEMP}(1,1,ZZ,1) + Fc_{p3} \cdot \text{TEMP}(1,1,ZZ,1) + Fc_{p4} \cdot \text{TEMP}(1,1,ZZ,1) \\
& + Fc_{p5} \cdot \text{TEMP}(1,1,ZZ,1) + Fc_{p6} \cdot \text{TEMP}(1,1,ZZ,1)
\]

\[
\text{Fvis} = F\nu_1 + F\nu_2 \cdot \text{TEMP}(1,1,ZZ,1) + F\nu_3 \cdot \text{TEMP}(1,1,ZZ,1) + F\nu_4 \cdot \text{TEMP}(1,1,ZZ,1) + F\nu_5 \cdot \text{TEMP}(1,1,ZZ,1) \\
& + F\nu_6 \cdot \text{TEMP}(1,1,ZZ,1) + F\nu_7 \cdot \text{TEMP}(1,1,ZZ,1)
\]

\[
\text{Fk} = Fk_1 + Fk_2 \cdot \text{TEMP}(1,1,ZZ,1) + Fk_3 \cdot \text{TEMP}(1,1,ZZ,1) + Fk_4 \cdot \text{TEMP}(1,1,ZZ,1) \\
& + Fk_5 \cdot \text{TEMP}(1,1,ZZ,1)
\]

\[
\text{Fum} = Vdot \cdot 4/(3.14 \cdot \text{PipeDi} \cdot \text{PipeDi} \cdot \text{PipeNumX} \cdot \text{PipeNumY})
\]

\[
\text{FRe} = \text{Fdensity} \cdot \text{Fum} \cdot \text{PipeDi} / \text{Fvis}
\]

\[
\text{IF (FRe.LT.(2300.0)) THEN}
\text{FRe}=2300.0
\text{ENDIF}
\]

\[
\text{FPr} = \text{Fvis} \cdot Fc_{p} / Fk
\]

\[
squiggle=1/((1.82*(\text{LOG10(FRe)})-1.64)*(1.82*(\text{LOG10(FRe)})-1.64))
\]

\[
\text{FNu} = (\text{squiggle}/8) \cdot (\text{FRe}-1000) \cdot \text{FPr} \cdot (1+((\text{PipeDi}/ZSpace)**(2/3))) \\
&/(1+12.7*(\text{SQRT(squiggle/8)})*((\text{FPr}**(2/3))-1))
\]

\[
h=(\text{FNu} \cdot Fk) / \text{PipeDi}
\]

\[
\text{IF(Vdot.EQ.(0.0)) THEN}
\text{h}=0.0
\text{ENDIF}
\]
DO 6 XX=2,(NodeX-1)

TEMP(XX,NodeY,ZZ,2)=TEMP(XX,NodeY,ZZ,1)+alpha*deltat*(
&(TEMP(XX+1,NodeY,ZZ,1)+TEMP(XX-1,NodeY,ZZ,1)-
&2*TEMP(XX,NodeY,ZZ,1))/Xspace*Xspace
&+(2*TEMP(XX,NodeY-1,ZZ,1)-2*TEMP(XX,NodeY,ZZ,1))
&(Yspace*Yspace))

6 CONTINUE

IF ((FluidNodeX+2).LE.(NodeX-1)) THEN
DO 66 XX=(FluidNodeX+2),(NodeX-1)

TEMP(XX,1,ZZ,2)=TEMP(XX,1,ZZ,1)+alpha*deltat*(
&(TEMP(XX+1,1,ZZ,1)+TEMP(XX-1,1,ZZ,1)-2*TEMP(XX,1,ZZ,1))/
&(Xspace*Xspace)+(2*TEMP(XX,2,ZZ,1)-2*TEMP(XX,1,ZZ,1))
&(Yspace*Yspace))

66 CONTINUE
ENDIF

IF ((FluidNodeY+2).LE.(NodeY-1)) THEN
DO 7 YY=(FluidNodeY+2),(NodeY-1)

TEMP(1,YY,ZZ,2)=TEMP(1,YY,ZZ,1)+alpha*deltat
&*((2*TEMP(2,YY,ZZ,1)-2*TEMP(1,YY,ZZ,1))/(Xspace*Xspace)
&+(TEMP(1,YY+1,ZZ,1)+TEMP(1,YY-1,ZZ,1)-2*TEMP(1,YY,ZZ,1))
&(Yspace*Yspace))

7 CONTINUE

ENDIF
**
* Calculates next timesstep Temperatures along Right
**

DO 78 YY=2,(NodeY-1)
TEMP(NodeX,YY,ZZ,2)=TEMP(NodeX,YY,ZZ,1)+alpha*deltat*(
&(2*TEMP(NodeX-1,YY,ZZ,1)-2*TEMP(NodeX,YY,ZZ,1))
&(Xspace*Xspace)+(TEMP(NodeX,YY+1,ZZ,1)
&+TEMP(NodeX,YY-1,ZZ,1)-2*TEMP(NodeX,YY,ZZ,1))
/(Yspace*Yspace))
78 CONTINUE

**
* Calculates next timesstep Temperatures for interior
**

DO 8 XX=2,(NodeX-1)
DO 9 YY=2,(NodeY-1)

IF ((XX.GE.(FluidNodeX+2)).OR.(YY.GE.(FluidNodeY+2))) THEN
TEMP(XX,YY,ZZ,2)=TEMP(XX,YY,ZZ,1)+alpha*deltat
&*((TEMP(XX+1,YY,ZZ,1)+TEMP(XX-1,YY,ZZ,1)-2
&*TEMP(XX,YY,ZZ,1))/(Xspace*Xspace)+(TEMP(XX,YY+1,ZZ,1)
&+TEMP(XX,YY-1,ZZ,1)-2*TEMP(XX,YY,ZZ,1))/(Yspace*Yspace))
ENDIF
9 CONTINUE
8 CONTINUE

**
* Calculate next timesstep Temperatures at the corners
**

TEMP(1,NodeY,ZZ,2)=TEMP(1,NodeY,ZZ,1)+alpha*deltat*(
&(2*TEMP(2,NodeY,ZZ,1)-2*TEMP(1,NodeY,ZZ,1))/(Xspace*Xspace)
&+(2*TEMP(1,NodeY-1,ZZ,1)-2*TEMP(1,NodeY,ZZ,1))
&/(Yspace*Yspace))
TEMP(NodeX,1,ZZ,2)=TEMP(NodeX,1,ZZ,1)+alpha*deltat*
&(2*TEMP(NodeX-1,1,ZZ,1)-2*TEMP(NodeX,1,ZZ,1))/(Xspace*Xspace)
&+(2*TEMP(NodeX,2,ZZ,1)-2*TEMP(NodeX,1,ZZ,1))/(Yspace*Yspace)

TEMP(NodeX,NodeY,ZZ,2)=TEMP(NodeX,NodeY,ZZ,1)+alpha*deltat*
&*((2*TEMP(NodeX-1,NodeY,ZZ,1)-2*TEMP(NodeX,NodeY,ZZ,1))
&(Xspace*Xspace)+(2*TEMP(NodeX,NodeY-1,ZZ,1)-2
&*TEMP(NodeX,NodeY,ZZ,1))/(Yspace*Yspace))

**
* Calculate next timestep Temperatures at the fluid/storage interface
**

TEMP(1,FluidNodeY+1,ZZ,2)=TEMP(1,FluidNodeY+1,ZZ,1)+h*deltat*
&*(Temp(1,FluidNodeY+2,ZZ,1)-TEMP(1,FluidNodeY+1,ZZ,1))
&/(rhoalpha*cpalpha*Yspace)+Sk*deltat*((TEMP(1,FluidNodeY,ZZ,1)
&+TEMP(1,FluidNodeY+2,ZZ,1)-2*TEMP(1,FluidNodeY+1,ZZ,1))
&/(Yspace*Yspace)+(2*TEMP(2,FluidNodeY+1,ZZ,1)
&-2*TEMP(1,FluidNodeY+1,ZZ,1))/(Xspace*Xspace)
&/(rhoalpha*cpalpha*Zspace)

TEMP(FluidNodeX+1,1,ZZ,2)=TEMP(FluidNodeX+1,1,ZZ,1)
&+(h*deltat/(rhoalpha*cpalpha*Xspace))*((TEMP(FluidNodeX,1,ZZ,1)
&-TEMP(FluidNodeX+1,1,ZZ,1))+(Sk*deltat/(rhoalpha*cpalpha*ZSpace))
&*((TEMP(FluidNodeX+1,ZZ,1)+TEMP(FluidNodeX+2,1,ZZ,1)
&-2*TEMP(FluidNodeX+1,1,ZZ,1))/(Xspace*XSpace)
&+(2*TEMP(FluidNodeX+1,2,ZZ,1)-2*TEMP(FluidNodeX+1,1,ZZ,1))
&/(YSpace*YSpace))

IF (FluidNodeX.GT.1) THEN
  DO 343 XX=2,FluidNodeX
  TEMP(XX,FluidNodeY+1,ZZ,2)=TEMP(XX,FluidNodeY+1,ZZ,1)
END
&+h*deltat*(TEMP(XX,FluidNodeY,ZZ,1)-TEMP(XX,FluidNodeY+1,ZZ,1))
&/(rhoalpha*cpalpha*YSpace)+(Sk*deltat/(rhoalpha*cpalpha*Zspace))
&*((TEMP(XX,FluidNodeY,ZZ,1)+TEMP(XX,FluidNodeY+2,ZZ,1)
&-2*TEMP(XX,FluidNodeY+1,ZZ,1))/(YSpace*YSpace)
&+(TEMP(XX-1,FluidNodeY+1,ZZ,1)+TEMP(XX+1,FluidNodeY+1,ZZ,1))
&-2*TEMP(XX,FluidNodeY+1,ZZ,1))/(XSpace*XSpace))
343 CONTINUE
ENDIF

IF (FluidNodeY.GT.1) THEN
DO 344 YY=2,FluidNodeY
TEMP(FluidNodeX+1,YY,ZZ,2)=TEMP(FluidNodeX+1,YY,ZZ,1)
&+h*deltat*(TEMP(FluidNodeX,YY,ZZ,1)-TEMP(FluidNodeX+1,YY,ZZ,1))
&/(rhoalpha*cpalpha*YSpace)+(Sk*deltat/(rhoalpha*cpalpha*Zspace))
&*((TEMP(FluidNodeX+1,YY-1,ZZ,1)+TEMP(FluidNodeX+1,YY+1,ZZ,1)
&-2*TEMP(FluidNodeX+1,YY,ZZ,1))/(YSpace*YSpace)
&+(TEMP(FluidNodeX,YY,ZZ,1)+TEMP(FluidNodeX+2,YY,ZZ,1))
&-2*TEMP(FluidNodeX+1,YY,ZZ,1))/(XSpace*XSpace))
344 CONTINUE
ENDIF

* New Fluid Temp Calc
**
SolidTempAVG1=0.0
SolidTempAVG2=0.0
Do 833 XX=1,NodeX
Do 834 YY=1,NodeY
IF((XX.GT.FluidNodeX).OR.(YY.GT.FluidNodeY))THEN
SolidTempAVG1=Temp(XX,YY,ZZ,1)+SolidTempAVG1
SolidTempAVG2=Temp(XX,YY,ZZ,2)+SolidTempAVG2
ENDIF
834 CONTINUE
833 CONTINUE

SolidTempAVG1=SolidTempAVG1/(NodeX*NodeY-FluidNodeX
& *FluidNodeY)
SolidTempAVG2=SolidTempAVG2/(NodeX*NodeY-FluidNodeX
& *FluidNodeY)
& *FluidNodeY)

cpSAvg1=Scp1+Scp2*SolidTempAVG1+Scp3*SolidTempAVG1*SolidTempAVG1
& +Scp4*SolidTempAVG1
& *SolidTempAVG1*SolidTempAVG1

VGl

cpSAvg2=Scp1+Scp2*SolidTempAVG2+Scp3*SolidTempAVG2*SolidTempAVG1
& +Scp4*SolidTempAVG2
& *SolidTempAVG2*SolidTempAVG2

VGl

rhoSAvg1=Srho1+Srho2*SolidTempAVG1+Srho3*SolidTempAVG1
& *SolidTempAVG1+Srho4*SolidTempAVG1
& *SolidTempAVG1*SolidTempAVG1

VGl

rhoSAvg2=Srho1+Srho2*SolidTempAVG2+Srho3*SolidTempAVG2
& *SolidTempAVG2+Srho4*SolidTempAVG2
& *SolidTempAVG2*SolidTempAVG2

AvgSolidEnergy1=cpSAvg1*rhoSAvg1*SolidTempAVG1*((PipeSpaceX
& -PipeDo)/2)*((PipeSpaceX-PipeDo)/2)*Zspace

AvgSolidEnergy2=cpSAvg2*rhoSAvg2*SolidTempAVG2*((PipeSpaceX
& -PipeDo)/2)*((PipeSpaceX-PipeDo)/2)*Zspace

cpf=Fcp1+Fcp2*Temp(1,1,ZZ,1)+Fcp3*Temp(1,1,ZZ,1)*Temp(1,1,ZZ,1)
& +Fcp4*Temp(1,1,ZZ,1)
& *Temp(1,1,ZZ,1)*Temp(1,1,ZZ,1)

rhof=Frho1+Frho2*Temp(1,1,ZZ,1)+Frho3*Temp(1,1,ZZ,1)
& *Temp(1,1,ZZ,1)+Frho4*Temp(1,1,ZZ,1)
& *Temp(1,1,ZZ,1)*Temp(1,1,ZZ,1)

Vf=3.14*ZSpace*PipeDi*PipeDi/16

Temp(1,1,ZZ,1)=(AvgSolidEnergy1-AvgSolidEnergy2)
& /(cpf*rhof*Vf)+Temp(1,1,ZZ,1)

**
* Calculates next Z-node Fluid Temperature
**

cpř=Fcp1+Fcp2*Temp(1,1,ZZ,1)+Fcp3*Temp(1,1,ZZ,1)*Temp(1,1,ZZ,1)
&+Fcp4*Temp(1,1,ZZ,1)*Temp(1,1,ZZ,1)*Temp(1,1,ZZ,1)
\[ \rho_0 = \rho_0^1 + \rho_0^2 \times \text{Temp}(1,1,ZZ,1) + \rho_0^3 \times \text{Temp}(1,1,ZZ,1) \]
& \times \text{Temp}(1,1,ZZ,1) + \rho_0^4 \times \text{Temp}(1,1,ZZ,1) \times \text{Temp}(1,1,ZZ,1) \times \text{Temp}(1,1,ZZ,1) \]

\[ \text{Volf} = 3.14 \times \text{PipeDi} \times \text{PipeDi} \times ZSpace / 16 \]

\[ \text{IF (ZZ.EQ.1) THEN} \]
\[ \text{Temp}(1,1,ZZ,2) = (\text{TempIN} \times \text{Vdot} / (4 \times \text{PipeNumX} \times \text{PipeNumY}) \times \text{deltat} \]
& \times \text{Temp}(1,1,ZZ,1) \]
& \times (\text{Volf} - \text{Vdot} / (4 \times \text{PipeNumX} \times \text{PipeNumY}) \times \text{deltat})) \]
& \text{Volf} \]

\[ \text{ELSE} \]
QQ=ZZ-1
\[ \text{Temp}(1,1,ZZ,2) = (\text{Temp}(1,1,QQ,1) \times \text{Vdot} / (4 \times \text{PipeNumX} \times \text{PipeNumY}) \]
& \times \text{deltat} + \text{Temp}(1,1,ZZ,1) \]
& \times (\text{Volf} - \text{Vdot} / (4 \times \text{PipeNumX} \times \text{PipeNumY}) \times \text{deltat})) \]
& \text{Volf} \]

\[ \text{ENDIF} \]

\[ \text{DO 444 XX=1,FluidNodeX} \]
\[ \text{DO 445 YY=1,FluidNodeY} \]
\[ \text{TEMP}(XX,YY,ZZ,2) = \text{Temp}(1,1,ZZ,2) \]
445 CONTINUE
444 CONTINUE
5 CONTINUE

**
* Resets Array for next internal timestep
**

\[ \text{DO 61 XX=1,NodeX} \]
\[ \text{DO 62 YY=1,NodeY} \]
\[ \text{DO 63 ZZ=1,NodeZ} \]

\[ \text{Temp}(XX,YY,ZZ,3) = \text{Temp}(XX,YY,ZZ,1) + \text{Remain} \times (\text{Temp}(XX,YY,ZZ,2) \]
& \times -\text{Temp}(XX,YY,ZZ,1)) \]

\[ \text{Temp}(XX,YY,ZZ,1) = \text{Temp}(XX,YY,ZZ,2) \]
63 CONTINUE
62 CONTINUE
61 CONTINUE
77 CONTINUE

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**
* Resets Array for next timestep
**

DO 51 XX=1,NodeX
DO 52 YY=1,NodeY
DO 53 ZZ=1,NodeZ

Temp(XX,YY,ZZ,1)=Temp(XX,YY,ZZ,3)

53 CONTINUE
52 CONTINUE
51 CONTINUE

**
* Determines the amount of Energy associated with the given temperatures for the fluid and solid
**

EF(2)=0.0
ES(2)=0.0

STempAVG2=0.0
FTempAVG2=0.0
Do 987 XX=1,NodeX
Do 988 YY=1,NodeY
Do 989 ZZ=1,NodeZ

IF((XX.GT.FluidNodeX).OR.(YY.GT.FluidNodeY))THEN
STempAVG2=Temp(XX,YY,ZZ,1)+STempAVG2
ELSE
FTempAVG2=Temp(XX,YY,ZZ,1)+FTempAVG2
ENDIF

989 CONTINUE
988 CONTINUE
987 CONTINUE

STempAVG2=STempAVG2/(NodeX*NodeY*NodeZ-FluidNodeX & *FluidNodeY*NodeZ)
FTempAVG2=FTempAVG2/(FluidNodeX & *FluidNodeY*NodeZ)
cpSAvg2=Scp1+Scp2*STempAVG2+Scp3*STempAVG2*STempAVG2 & +Scp4*STempAVG2 & *STempAVG2*STempAVG2

cpFAvg2=Fcp1+Fcp2*FTempAVG1+Fcp3*FTempAVG1*FTempAVG2 & +Fcp4*FTempAVG2 & *FTempAVG2*FTempAVG2

rhoSAvg2=Srho1+Srho2*STempAVG2+Srhol*STempAVG2 & *STempAVG2+Srhol*STempAVG2 & *STempAVG2*STempAVG2

rhoFAvg2=Frho1+Frho2*FTempAVG2+Frho3*FTempAVG2 & *FTempAVG2+Frho4*FTempAVG2 & *FTempAVG2*FTempAVG2

ES(2)=cpSAvg2*rhoSAvg2*STempAVG2*(Length-PipeDo/2) &*(Width-PipeDo/2)*Depth

EF(2)=cpFAvg2*rhoFAvg2*FTempAVG2*(PipeDo/2) &*(PipeDo/2)*Depth*3.14

DeltaEf=Ef(2)-Ef(1)
DeltaEs=Es(2)-Es(1)

**
* Availability Calculation based on Input/EXIT Temps
**

TEMPIN=FTEMPIN
TEMPOUT=Temp(1,1,NodeZ,3)
Tref=290.0

Availability=(Fcp1*TEMPOUT+Fcp2*TEMPOUT &*TEMPOUT/2+Fcp3+TEMPOUT &*TEMPOUT*TEMPOUT/3+Fcp4 &*TEMPOUT*TEMPOUT*TEMPOUT &*TEMPOUT/4)-(Fcp1*TEMPIN+Fcp2 &*TEMPIN*TEMPIN/2+Fcp3+TEMPIN &*TEMPIN*TEMPIN/3+Fcp4*TEMPIN &*TEMPIN*TEMPIN*TEMPIN/4)-Tref &*(Fcp1*LOG(TEMPOUT)+Fcp2*TEMPOUT+Tref &*TEMPOUT*TEMPOUT/2+Fcp4 &*TEMPOUT*TEMPOUT*TEMPOUT/3) &-(Fcp1*LOG(TEMPIN)+Fcp2*TEMPIN+Fcp3

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&*TEMPIN*TEMPIN/2+Fcp4*TEMPIN
&*TEMPIN*TEMPIN/3))

**
* Outputs
**
WRITE(*,*) TEMPIN, "", TEMPOUT, "", Es(1), "", Es(2), "", DeltaEs, ""
& Ef(1), "", Ef(2), "", DeltaEf, "", Availability
WRITE(3,*) TEMPIN, "", TEMPOUT, "", Es(1), "", Es(2), "", DeltaEs, ""
& Ef(1), "", Ef(2), "", DeltaEf, "", Availability

GOTO 800

665 CLOSE (UNIT=2)
CALL FDATE(STRING)
WRITE(*,*) "Program Ended on:"
WRITE(*,*) STRING
WRITE(3,*) "Program Ended on:"
WRITE(3,*) STRING
CLOSE (UNIT=3)

666 END PROGRAM
Figure 23 illustrates the actual storage system being modeled. The physical dimensions and properties of the storage system are controlled through user-defined inputs.

Once the actual system's information has been entered into the program, divisions of symmetry are made to reduce the volume of storage on which the calculations will be performed. Figure 24 shows the first set of divisions made.
The storage system has been divided into smaller, identical subsections. One of these subsections is then further reduced through axis of symmetry as shown in Figure 25.
Subsection of Storage System further divided into quarter sections through use of Symmetry

One of the subsections from the reduction is then overlaid with the user defined nodal system. The subsection is divided into elements along the Z-axis equal to the number of nodes specified for the Z direction as shown in Figure 26.

Each of the Z-axis elements then has the user defined XY nodal system overlaid as shown in Figure 27. With this step, the nodal structure has been established and calculations can begin.
Figure 27  User defined nodal system overlaid into each Z-axis slice.

● = a single node
Display Increment Example

Simulation time increments are user defined. The larger the time increment, the more drastic the calculated changes may be. By decreasing the time increment, the calculated results can be refined for a better understanding of the system interaction. More detail can also be obtained by decreasing the axis time span on user-generated graphs as illustrated in Figures 28 and 29.

Equal Energy Storage Capacities - System 1 and 2

Figure 28 Display of Fig.8 with 24 Hour Axis Scale.
Figure 29  Display of Fig.8 with Smaller Axis Increment.
REFERENCES


VITA

Graduate College
University of Nevada, Las Vegas

Jason Mulvey

Home Address:
5612 Royal Castle Lane
Las Vegas, Nevada 89130

Degrees:
Bachelor of Science, Mechanical Engineering, 1999
University of Nevada, Las Vegas

Thesis Title: Second Law Analysis of the Transient Behavior of Solid Media Thermal Storage Utilizing Finite Difference Computational Modeling

Thesis Examination Committee:
Chairperson, Dr. Robert Boehm, Ph. D.
Committee Member, Dr. Darrell Pepper, Ph. D.
Committee Member, Dr. William Culbreth, Ph. D.
Graduate Faculty Representative, Dr. Yahia Baghzouz, Ph. D.