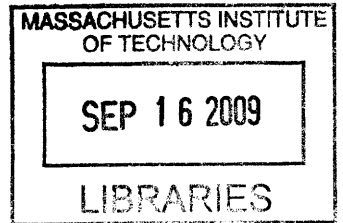# Modeling a Solar Energy Collector With an Integrated Phase-Change Material

by

Alexander Adrian Guerra

Submitted to the Department of Mechanical Engineering
in partial fulfillment of the requirements for the degree of

Bachelor of Science in Mechanical Engineering

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Abstract

In this thesis, a finite-element computer model was created to simulate a solar air heater with an integrated-phase change material. The commercially available finite-element package ADINA-Fluid was used to generate the model that captures the fundamental physical processes which are necessary in accurately simulate the system. These processes include convective and radiative losses between the working fluid and device. Time varying loads to simulate the available solar energy that can be collected over the course of a day. Most importantly the phase-change material. This was accomplished by defining a material with a temperature-dependent specific heat. The simulation yielded positive results to its validity and can now be used to test different physical geometries and material before a prototype of the solar air heater is produced.

Thesis Supervisor: John H. Lienhard V
Title: Collins Professor of Mechanical Engineering

Acknowledgments

My mother, father, and brothers for all their patience during my time at MIT.

Prof. Lienhard and Ed Summers for their time and willingness to work with me.

Kiersten Pollard for keeping me sane.

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Chapter 1

Introduction

The goal of this thesis is to create a computer model that effectively simulates a solar air heater with an integrated phase-change material(PCM). As seen in Fig (1-1) the heater is essentially an air channel sandwiched between a glazing and absorber plate. Beneath the absorber plate a layer of PCM and insulation are present.

Energy from the sun is transmitted through the glazing plate and is absorbed by the absorber plate. Solar energy heats the PCM as well as the moving fluid in the channel. By the time the working fluid exits the device its temperature is higher than when it entered. The collection of solar energy is dependent on the position of the sun, heat flux on the absorber is non-uniform. The phase-change material acts as a thermal battery. When the heat flux is high enough to melt the PCM energy is stored during this phase-change. When the heat flux begins to wain the solidification of the PCM releases energy into the moving fluid maintaining a high exit temperature.

The creation of the computer model required the implementation of several key physical processes. The first was the inclusion of thermal loss mechanisms to the environment from the device. The second was heat transfer processes taking place between the absorber and glazing plates such as radiation effects between the plates and forced convection due to the moving fluid. The final physical process modeled was the phase-change material.
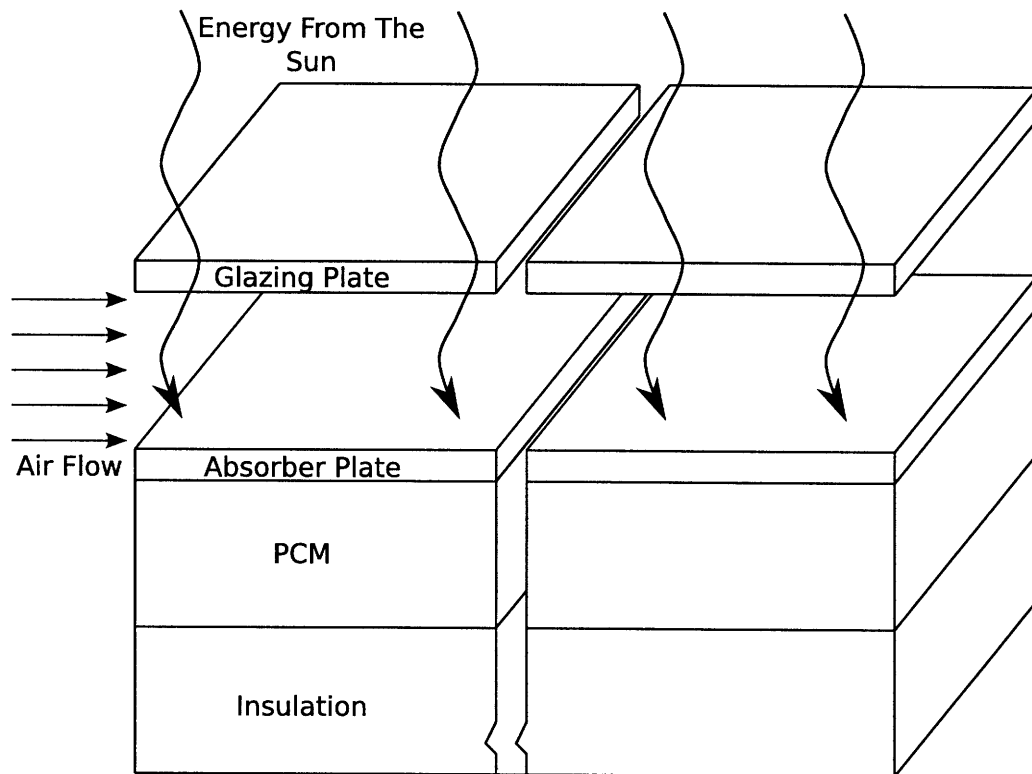
Figure 1-1: A simple schematic of the device that was modeled in ADINA-F. Energy from the sun strikes the top of the absorber plate and is either transferred to the moving air between the the absorber and glazing plates or enters the phase-change material.

1.1 Motivations

The creation of a model that accurately predicts the effect that changes in system geometries and materials have on the final state is invaluable during the design process. Such a model enables the designer to 'test' geometries and materials without the time consuming and expensive process of constructing many bench level experiments. In the specific case of the solar air heater the phase-change material has yet to be chosen. This model will be used to evaluate various designs to aid in the construction of a prototype.

1.2 Modeling

A model need not be a complex simulation of all physical processes governing a device's interaction with the world. In its most basic form, a model can simply be an equation that gives meaningful results when solved. A simple example would be the equations of motion that describe the movement of a pendulum. With the application of some basic physics a simulation of the object can be created. The effect on a pendulum's motion for different masses and string lengths can be seen from these equations without the need to build and test physical pendulums. In this way insight into important design parameters can be gained.

The creation of an accurate model must be done carefully. Knowing when approximations can be made and what physical processes can be ignored is important in both the creation of a model and evaluating the results it gives. Returning to the previous example the validity of the pendulum model is a function of the assumptions made during its creation. In most introductory physics classes the small angle approximation $\sin\theta \cong \theta$ is used to greatly reduce the complexity of the differential equation that describes the motion of the pendulum. This assumption is useful but the user of the model must be mindful of the assumption in place. If the model is applied to a situation where the assumptions do not hold or where physical processes required for accuracy have been neglected the results may

be far from the reality.

Unfortunately the application of simple equations is often incapable of describing an entire system. As the complexity of the system increases sophisticated tools and models are needed to efficiently produce an analysis. Finite-element analysis is one of these sophisticated tools. The finite-element method is the process of breaking down a physical simulation into small elements to which algebraic equations can be applied and solved for, instead of explicitly solving complex partial differential equations. As the size of the elements used decreases the closer the results converge on the actual solution. The drawback of the finite analysis method is that the method is computationally intensive due to the large number of elements needed. Therefore a computer and efficient algorithms are needed to run a successful finite analysis model.

1.3 Tools

The primary tool used to develop the computer model discussed in this paper was the FEA package ADINA-Fluids [1]. ADINA-F was chosen because it can perform analysis on moving fluids, and include heat transfer effects. Unfortunately, ADINA-F had many limitations when conducting a heat transfer analysis primarily in the application of forced convection heat transfer coefficients, and radiation between two surfaces. The final model generated required the application of some creative boundary conditions to overcome the limitations of ADINA-F and are described in Chapter 2.

Chapter 2

Model

The primary goal of this thesis was the creation of a computer model to simulate a novel solar air heating device with an integrated phase-change material. The commercial finite-element package ADINA-F was the primary tool used to generate a working model. Due to the complex nature of simulating the device completely (i.e. turbulent flow, forced convection, and radiative heat transfer) modeling choices were made to reduce computational complexity of the simulation. The development of the computational model in ADINA can be broken into the following seven steps.

1. Analysis Assumptions

2. Geometry

3. Materials

4. Loads and Boundary Conditions

5. Element Groups

6. Meshing

7. Run Analysis

This roadmap is not a linear path that lead to the final model. Each step was revisited several times as design choices were tested and finalized.

2.1 Analysis Assumptions

Defining basic analysis assumptions in ADINA-F is necessary if a working model is going to be produced. ADINA-F by default does not include heat transfer in its analysis. If the model is to produce meaningful results ADINA must include heat transfer.

The second major assumption was that fluid flow in the channel would be slug flow with no velocity profile. With a working fluid of air and an entrance velocity of $v \sim 2.3[\mathrm{m/s}]$ the flow in the channel would almost certainly have transitioned to turbulent flow. ADINA-F unfortunately does not allow the creation of temperature dependent materials in turbulent flow analysis which is needed to implement the phase-change material. Since the primary goal was to model the temperature distribution in the device the assumption was made and fluid velocity profiles were ignored. In this model the effect of turbulent fluid flow is only important in that it mixes the warm air with cool air in the channel producing a more accurate bulk temperature. If the fluid is laminar the low thermal conductivity of air would require very high temperatures to change the bulk temperature. The modeling of a turbulent system with a slug flow model involved approximating the bulk temperture and introducing heat transfer coefficients will be discussed later.

The final assumption defined the model as a two-dimensional system, based on the observation that a 3D analysis would be very similar to a 2D analysis. The geometry of the device as seen in Fig. (1-1) is symmetric along the width of the device. With the assumption that the velocity and temperature distributions will be the same along its cross-section at any position along the length of the device,the system is effectively two dimensional.

2.2 Geometry

With the basic analysis assumptions made the next step was entering the geometry of the device into the model. The most primitive construction element in ADINA is
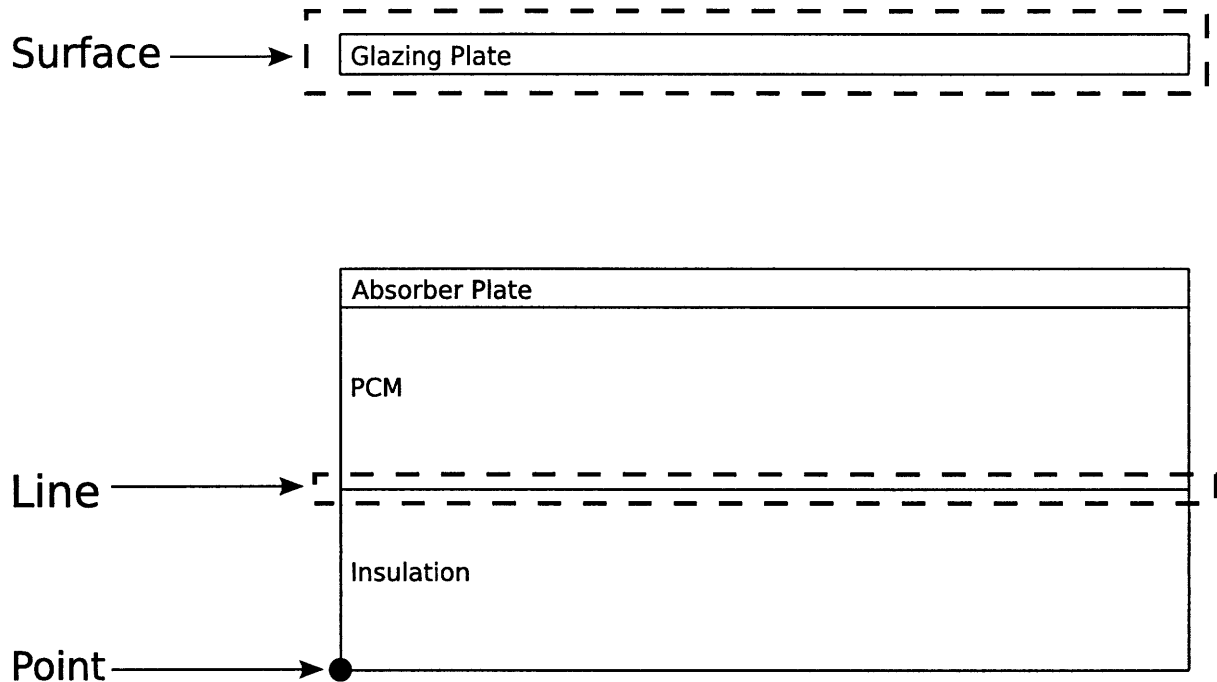
Surface ———► | Glazing Plate

Absorber Plate

PCM

Line ———►

Insulation

Point ———►●

Figure 2-1: The basic geometric elements used by ADINA are points,lines, and surfaces. Two points can be connected to form a line, and four lines can form a surface.

the point. Points are defined by their Cartesian positions on the YZ plane. From two points a line can be defined and from four lines a surface can be constructed. In ADINA-F lines and surfaces are incredibly important. Loads, boundary conditions, initial conditions, and constraints are applied to these geometric elements. Surfaces also form the basis of element groups which will be explored in Section 2.5.

The solar heater went through various stages of geometric evolution but the final dimensions can be seen in Fig. (2-1). The power of an accurate computer model, such as the one described here, is that geometries can be easily changed to run a new analysis.

2.3   Materials

For ADINA to run an analysis it must have material properties that can be applied to geometric elements in the model. ADINA breaks materials into two types: temperature-dependent and temperature-independent materials.

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2.3.1 Solids

As seen in Fig. (1-1) the solid elements in the device are the insulator, phase-change material, absorber plate, and glazing plate. The addition of materials with constant properties to ADINA's material database requires entering the properties into the appropriate text fields. The material properties used for this simulation can be found in Table(A.1)

For the model to be accurate, heat transfer by forced convection and radiation between the absorber and glazing plates needed to be included. Because ADINA-F does not have the ability to implement convection with a nodally dependent far field temperature or radiation between two surfaces a workaround was implemented by defining "dummy" materials to capture the effects of convection and radiation in the model. The two "dummy" materials sandwiching the working fluid. One is located above the absorber plate and the other is below the glazing plate. Fig. (2-3) shows their location.

Correlations were used to find values for the heat transfer coefficients h_{rad} and $h_{convection}$ for a range of temperatures. Two temperature-dependent materials were defined with negligible heat capacity $c_p \sim 1 \times 10^{-20}$ and a thermal conductivity k from Eqn.(2.1) where l is the thickness of the "dummy" material.

$$k = h_{total}l \tag{2.1}$$

The heat transfer corfficinet used in the previous equation is the sum of the radiative and convevective heat transfer coefficients. $h_{convection}$ was found to be a constant for all tempertures. The values used in this model were $h_{convectionAbsorber} = 84.85$ and $h_{convectionGlazing} = 13.98$.

$$h_{total} = h_{radiation} + h_{convection} \tag{2.2}$$

h_{rad} for the absorber and glazing plate was found in a two step process. First an estimation of the radiation heat flux from the absorber plate to the glazing plate

was made and found to very almost linearly with the imposed heat flux from the sun. A negative heat flux was applied to the top of the absorber "dummy" material to simulate radiative losses, and a matching positive heat flux was applied to the bottom of the glazing "dummy" material to simulate the transfer of energy between the two plates.

The first step limits radiative heat transfer to when their is a positive solar heat flux being applied. If the model is to be accurate during the night radiation must be independent of the imposed solar flux. The second step was to encapsulate the radiative heat transfer process into a heat transfer coefficient. The temperature difference between the two plates was found to be small with a maximum of 5.16K and an average $\Delta T = 1.9396$K

$$h_{rPlate} = C \left(T^2 + (T - \Delta T)^2\right) (2T - \Delta T) \tag{2.3}$$

$$h_{rCover} = C \left(T^2 + (T + \Delta T)^2\right) (2T + \Delta T) \tag{2.4}$$

Eqn.(2.3) and Eqn.(2.4) were used to calculate the appropriate temperature-dependent heat transfer coefficients where $C = 1.5386 \times 10^{-7}$ and captures all the emissivities and radiation constants. [2]

The heat capacity was defined as negligible because the "dummy" materials did not contain any energy storage properties. They were to only act as temperature-dependent thermal resistors to model heat transfer.

2.3.2 Fluids

The working fluid in the model can have arbitrary material properties but air was chosen to be the working fluid for this analysis to observe a baseline response. The properties of air were added to the material database as being temperature-independent. Because ADINA-F has no knowledge of the material's phase at this stage in the simulation's development there is no difference between the defined materials except their values. The distinction between fluids and solids

was made during the construction of element groups and will be discussed in Section 2.5.

2.3.3 Phase-Change Material

The most interesting material defined in model was the phase-change material (PCM). The effect of having a PCM incorporated in this solar air heater is that a high output temperature can be maintained for much longer than if the design lacked a PCM. The PCM can be thought of as a thermal battery. Energy is needed to increase the PCM's temperature and to change the PCM from a solid to a liquid. During the process of solidification the material releases energy absorbed when melted. As energy from the sun is absorbed by the absorber plate the energy increases the temperature of the working fluid moving across the plate and the PCM underneath. If there is enough energy transferred to the PCM its temperature will increase and it will melt. At the end of the simulated day, when the energy being imparted by the sun decreases and the working fluid cools the absorber plate, the PCM releases energy during the solidification process and keeps the temperature of the working fluid relativity stable.

The PCM's material properties needed the ability to change as a function of temperature. A material was defined in ADINA-F as having a temperature dependent specific heat c_p defined by Eqn. (2.5) [2]. This piecewise function was added to the ADINA material database as a table of material properties for sixteen temperatures. ADINA then creates a material property curve from this table.

$$c_p = \begin{cases} c_{ps} & T \leq T_m \\ c_{pl} + \frac{H_{sf}}{\delta T} & T_m \leq T \leq T_m + \delta T \\ c_{pl} & T > T_m + \delta T \end{cases} \tag{2.5}$$

In Eqn. (2.5), c_{ps} and c_{pl} are the materials' specific heat in a solid and liquid state respectively. h_{sf} is the materials' latent heat and δT is the range over which each material undergoes the phase change. For this model δT was assumed to be

one degree kelvin. The density of the material was also modeled as being temperature depended.

2.4 Loads and Boundary Conditions

If a structure has no loading conditions applied to it and all elements are in equilibrium the transient analysis of the structure is relatively simple. Without a force to change the state of the system the system will for the most part remain in equilibrium. Therefore the next step was to apply the initial conditions, boundary conditions, and loads needed to revel the transient nature of the system.

The first step taken to model the movement of fluid through the device was to implement the wall boundary condition on lines in contact with the fluid (excluding the two perpendicular to fluid flow). ADINA-F can automatically implement a special boundary condition called 'wall'. This was added to the appropriator lines and the 'slip' condition was selected. With the slip condition activated the flow in the channel was modeled as inviscid. This was chosen because the fluid velocity profile is not important to this analysis. An entrance velocity was prescribed as a load on the line at the entrance of the channel perpendicular to fluid flow. The final condition applied to the fluid was a prescribed temperature of 303.15 K (30 °C) at the entrance of the channel.

To simulate the energy absorbed from the sun by the absorber plate during the day a time varying distributed heat flux q'' was applied to the line forming the upper surface of the absorber plate. The heat flux varies with time because the magnitude is proportional to the position of the sun in the sky. Fig. (2-2) is a graph of the heat flux as a function of time. As expected the peak is around the middle of the day.

The final boundary conditions applied to this model was the losses on the top and bottom of the device. A natural convection coefficient h_{bottom} for the bottom was applied with a far field temperature of T_∞. The top was given a temperature depended loss coefficient h_{top} with the same far field temperature. The
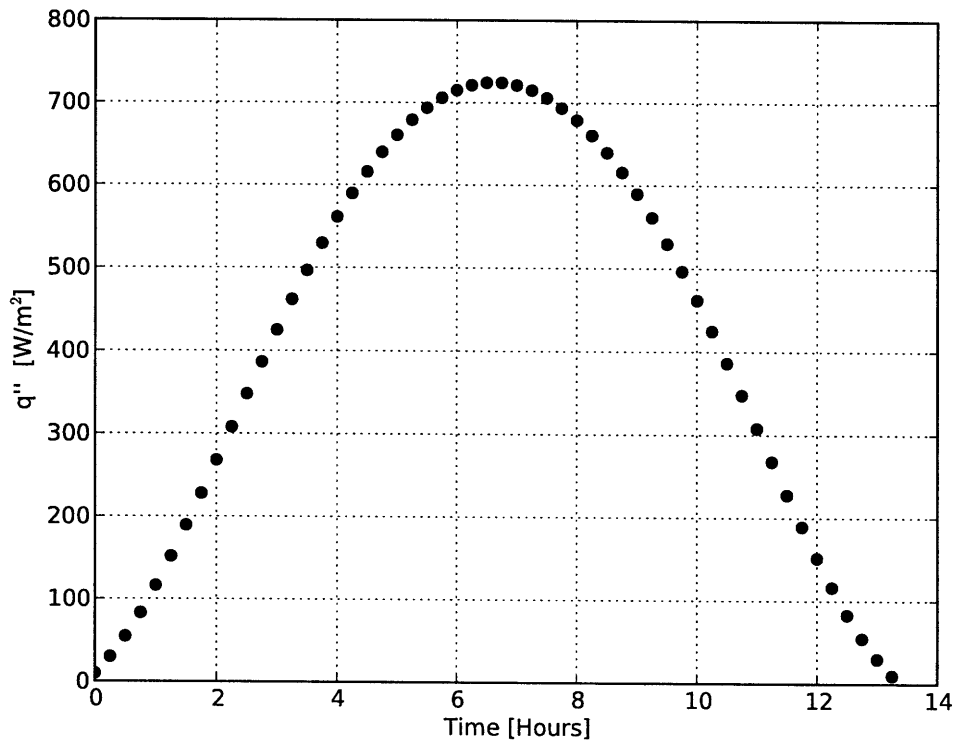
Figure 2-2: A distributed heat flux was applied to the top surface of the absorber plate. The graph shows the magnitude of heat flux as a function of time to simulate the changing position of the sun. As can be expected the peak happens around mid-day.

final model produced used a far field temperature of of $T_\infty = 303.15K$.

2.5 Element Groups

For ADINA-F to properly run the analysis it needs to link the geometry with the materials and analysis parameters. This is done by creating element groups. Each surface of the computer model was assigned its own element group and each element group was assigned a material. In addition to a material the element groups were set as either a two dimensional fluid or a solid. ADINA-F is now able to determine if a surface represents a solid or a fluid and what its material properties are. Fig. (2-3) shows the location and number of the element groups defined in the model.

The phase-change material was modeled as being a solid even when its temperature passed its melting point. This was done to simplify the simulation. In reality some form of mechanical matching element would be needed to compensate for the change in volume associated with the PCM melting and a gap forming between the absorber plate. The prototype would easily be able to compensate for this so there is no need to model this effect.

2.6 Meshing

The basis of all finite-element analysis is the creation of smaller sub-elements within the geometry in a process called meshing. As the size of the elements decrease the analysis will converge with the actual result. Unfortunately, as the number of elements in a mesh increase, so does the time needed to perform the analysis. A good mesh is one that balances an accurate result with a reasonable analysis run time. If the accuracy of a small mesh is adequate there is no need to increase the number of elements. Mesh quality is rather subjective and depends on the needed accuracy. For this model many mesh configurations were tried and the the final configuration used 7400 elements to model the system. The element group corresponding to the phase-change material contained the greatest number of
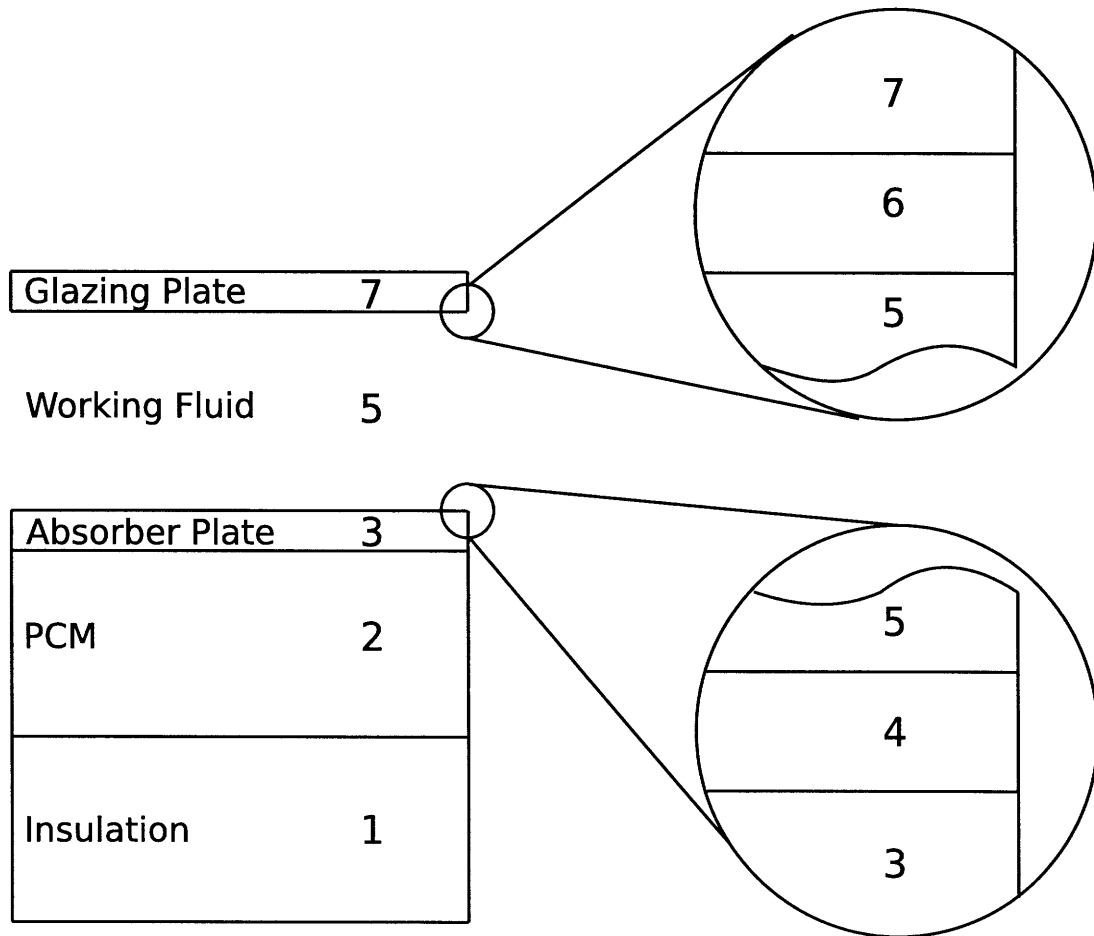
Figure 2-3: The two dimensional geometry of the device not to scale. Each number is an element group with a material assigned to it. The location of the negligibly thin dummy materials used to model the effects of radiative heat transfer between the plates and convection from the working fluid can be seen as elements 4 and 6.

elements to produce acurite information about what was happening in the phase-change material.

One of the initial analysis assumptions made in Section 2.1 was the fluid flow in the channel would be laminar. This assumption was made not because it fits the model but because ADINA-F has limitations when modeling turbulent flow. The method for working around ADINA-F's limitations was to add 'dummy' materials that carry all the fluids thermal resistance within their heat transfer coefficients. See section 2.3. A set of constraint equations was implemented to tie the nodal temperatures along the line bounding the bottom of the fluid channel to the nodes directly above them.

2.7   Run Analysis

The analysis for the transient response was run at 45 second time steps for 1000 steps giving a total of 12.5 hours of simulated data.

Chapter 3

Results

With a completed model in place the simulation was run and the output data was analyzed. Although the best way to validate this computer model would be to compare the simulated results with experimental data this is unfortunately not an option at this time. However, despite our inability to compare the modeled data to collected experimental data, there are markers that give an indication that this model behaves the way it should.

The first thing to verify is whether or not whether or not the simulation changed the temperature of the device over time. Fig.(3-1) clearly shows that this is the case. The response of the system at 35100 seconds shows bands of different temperatures along the surface to the model. The slope of the temperature bands on the insulator is very shallow and the bottom of the device stays at a relatively low temperature. Intuitively this is what would be expected from a material with a very low thermal conductivity. This figure also provides evidence that some of the boundary conditions imposed on the system are implemented correctly. For example the lowest temperature is at the entrance of the fluid flow channel. This makes sense because the inlet temperature of the fluid was prescribed to be 303.15K (30 °C).

It was also important to verify that the modeled phase change material was changing as expected. Fig.(3-2) shows a small piece of the total simulated geometry, but it provides a clear view of the melt front. The long uninterrupted lines are the boundaries of the element groups. The arrows indicate direction of

Figure 3-1: A temperature profile band plot at a time of 35100 seconds in the simulation. The entrance temperature can clearly be seen as remaining constant. The difference between the thermal properties of the materials can also be observed. Note the abrupt change between the phase-change material and the insulation. Changes in the insulation's temperature take much more time and energy than in the PCM because it has a small thermal conductivity.
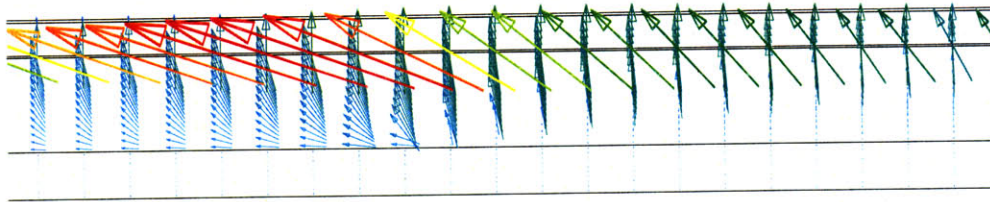

Figure 3-2: This picture was taken after the peak solar heat flux. The arrows direction indicate the direction of hear flux and the length is a marker of magnitude. Because the solar flux is decreasing the temperature of the exit fluid needs more energy to maintain a high temperature. Heat is then moved from the PCM into the fluid as evidenced by the direction of the arrows. The melt front occurs at the dramatic change in arrow length and orientation.

heat flux and their length is relative magnitude. This picture was taken at a time of 45000 seconds in the simulation and represents the device at the end of one day. The arrows in the phase-change material are all pointed in the direction of the working fluid. This is because the heat flux from the sun has is reduced decreasing the temperature of the moving fluid, and thermal energy moves from areas of high temperature to low temperature. Half-way through the figure an abrupt change in the the arrows is seen. This is the melt front. The area to the left of the melt front is solid and the area to the right is fluid.

The exit temperature versus time was the final marker of the model's correct behavior. Fig.(3-3) shows the fluid exit temperature versus time for one 24 hour
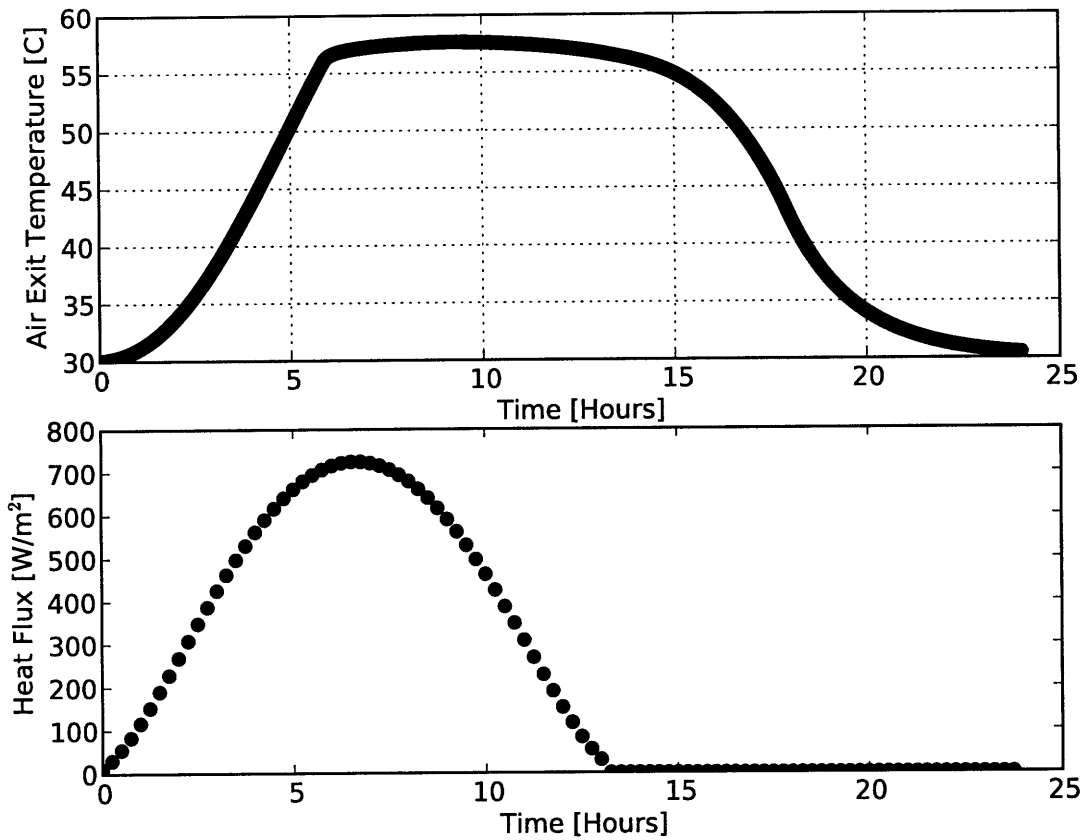
Figure 3-3: As the heat flux imparted to the absorber plate increases during the day the exit temperature begins to rise. Once the heat flux begins to fall in magnitude so to does the exit temperature, but the phase-change material present in the apparatus acts a a thermal battery. The temperature remains fairly high until the PCM solidifies completely and a shape drop in temperature is observed.

period. As expected the exit temperature begins to rise as the distributed heat flux increases.

Chapter 4

Conclusion and Future Work

4.1   Conclusion

The temperature profile, the magnitude of observed temperatures, and the heat flux provide strong evidence that the model presented in this paper accurately simulates the physical system, including all required physical processes. The first was the inclusion of thermal loss mechanisms to the environment from the device. The second process was heat transfer between the absorber and glazing plates including forced convection due to the moving fluid and radiation effects between the the plates. Now that a working model has been implemented effect geometry and material properties have on the system can be analysed.

The final runtime for a 1000 step analysis that simulates 48 hours takes approximately 15 minutes on an Intel Pentium 4 processor. This time is orders of magnitude smaller that the time needed to build a single model and collect data.

4.2   Future Work

This model relied heavily on the application of heat transfer correlations to simplify the the analysis and to work around some of the shortcomings found in the ADINA-Fluid software package. A more computationally complex model may be possible with other FEA packages. Running the simulation with a different and more

complex model from another FEA package might take longer but it could provide a comparison of the two models and verify the accuracy of this implementation.

Now that a working model has been generated the simulated results of different geometries and materials must be compared so the design specifications of the prototype can be reached and construction of an actual physical device can begin.

The analysis generated during this thesis is specific to the physical simulation being modeled. In particular the calculation of heat transfer correlations outside the software package makes this implementation tailor-made to suit the situation. However, the process used to develop the model is universal.

Appendix A

Tables

Material	Phase	k [W/mK]	μ[kg/s·m]	c_p [J/kgK]	ρ [kg/m^3]
Insulation	Solid	0.02	0	844	2500
Aluminum	Solid	160	0	900	2700
Air	Fluid	0.0257	0.00002	1005	1.205
Glass	solid	1	0	870	2470

Table A.1: This is a table of the material properties of the solid elements in the model.

Element Group	Purpose	Material Name	Element Type	Temp.-Dependent
1	Insulator	Insulation	Solid	No
2	PCM	Paraffin	Solid	Yes
3	Absorber Plate	Aluminum	Solid	No
4		'Dummy' Material 1	Solid	Yes
5	Working Fluid	Air	Fluid	No
6		'Dummy' Material 2	Solid	Yes
7	Glazing Plate	Glass	Solid	No

Table A.2: This table shows the components of the model with corresponding element properties and the materials implemented in the first model. The element type refers to either a two dimensional fluid or solid. Elements marked as being temperature depended must have materials defined as temperature dependent.

Temperature[K]	c_p[J/kgK]	k [W/mK]	ρ [kg/m^3]
1.0	2950.0	14.4456	818.0
50.0	2950.0	14.4456	818.0
100.0	2950.0	14.4456	818.0
150.0	2950.0	14.4456	818.0
200.0	2950.0	14.4456	818.0
300.0	2950.0	14.4456	818.0
330.149	2950.0	14.4456	818.0
330.15	2950.0	14.4456	818.0
331.149	2950.0	14.4456	818.0
331.15	228510.0	14.4456	818.0
332.15	228510.0	14.4456	760.0
332.151	2510.0	14.4456	760.0
350.0	2510.0	14.4456	760.0
400.0	2510.0	14.4456	760.0
500.0	2510.0	14.4456	760.0

Table A.3: This table was used to define a temperature-dependent material curve for the phase-change material.

Temperature[K]	c_p[J/kgK]	k [W/mK]	ρ [kg/m^3]
303	1.00E-020	0.01018	1.21
305	1.00E-020	0.01021	1.21
307	1.00E-020	0.01024	1.21
309	1.00E-020	0.01028	1.21
313	1.00E-020	0.01035	1.21
315	1.00E-020	0.01039	1.21
317	1.00E-020	0.01042	1.21
319	1.00E-020	0.01046	1.21
321	1.00E-020	0.01050	1.21
323	1.00E-020	0.01053	1.21
325	1.00E-020	0.01057	1.21
329	1.00E-020	0.01065	1.21
331	1.00E-020	0.01069	1.21
333	1.00E-020	0.01073	1.21
335	1.00E-020	0.01077	1.21
337	1.00E-020	0.01081	1.21

Table A.4: This table was used to define a temperature-dependent material curve for the "dummy" material that encapsulates forced convection and radiative heat transfer from the absorber plate.

Temperature[K]	c_p[J/kgK]	k [W/mK]	ρ [kg/m^3]
303	1.00E-020	0.00313	1.21
305	1.00E-020	0.00317	1.21
307	1.00E-020	0.00320	1.21
309	1.00E-020	0.00324	1.21
313	1.00E-020	0.00331	1.21
315	1.00E-020	0.00335	1.21
317	1.00E-020	0.00338	1.21
319	1.00E-020	0.00342	1.21
321	1.00E-020	0.00346	1.21
323	1.00E-020	0.00350	1.21
325	1.00E-020	0.00354	1.21
329	1.00E-020	0.00362	1.21
331	1.00E-020	0.00366	1.21
333	1.00E-020	0.00370	1.21
335	1.00E-020	0.00374	1.21
337	1.00E-020	0.00378	1.21

Table A.5: This table was used to define a temperature-dependent material curve for the "dummy" material that encapsulates forced convection and radiative heat transfer from the glazing plate.

Appendix B

Figures
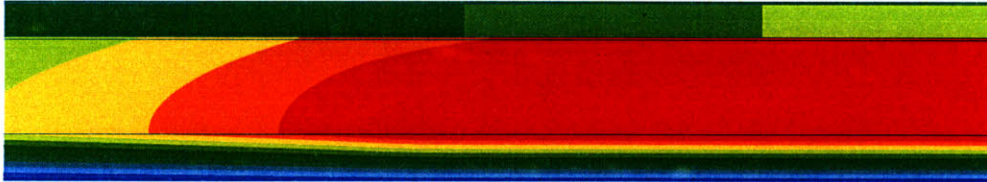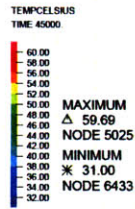
Figure B-1: Temperature band plot after 12 hours.

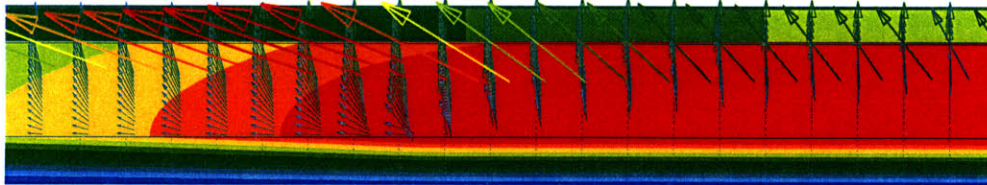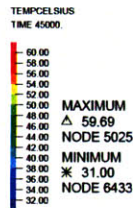Figure B-2: This is close up of the melt front.

Figure B-3: The melt front with a temperature band plot and a vector plot of the heat flux. The length of each vector corresponds to the magnitude of the heat flux at a point.
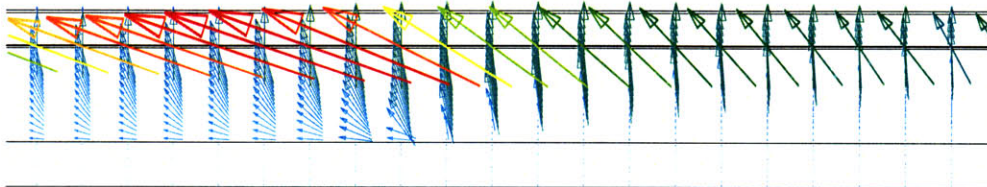

Figure B-4: A vector plot of the heat flux at the melt front. The length of each vector corresponds to the magnitude of the heat flux at a point.

Bibliography

[1] ADINA R & D Inc.

[2] Ed Summers. personal communication, 2009.