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Trade study of using phase change material in planetary entry vehicle

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TRADE STUDY OF USING PHASE CHANGE MATERIAL
IN PLANETARY ENTRY VEHICLE

A Thesis

Presented to

The Faculty of the Department of Mechanical and Aerospace Engineering
San Jose State University

In Partial Fulfillment
of the Requirement for Degree
Masters of Science

by

Amin H. Djamshidpour

May 2008

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Trade Study of using Phase Change Material in
Planetary Entry Vehicle

By

Amin H. Djamshidpour

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ABSTRACT

TRADE STUDY OF USING PHASE CHANGE MATERIAL IN PLANETARY ENTRY VEHICLE

by Amin H. Djamshidpour

Modeling and simulating of Phase Change Materials (PCMs) usage in shielding the Entry Vehicle during entry and save a part of thermal energy for future use is the main objective of this thesis. The first step toward the goal was the literature reviewed and two models of PCM-based cooling arrangement were selected as a benchmark. The first model is an experimental test unit, containing an energy storage tank, Bronze finned tube, PCM (water), pumps, and measurement devices. Heat transferred from PCM to the cold flowing fluid inside the tube causes solidification of PCM. The second model is the container built of Aluminum fins and Aristowax as PCM. Following the benchmark, a convective cooling on the top and a study heat load to the bottom side of the container were applied. By comparing the results of the benchmarks with the new obtained results, the new method was validated for simulating the PCMs. The main part of the study is a conceptual design of a heat shield based on PCM. In this part, initial and optimized design, including the benefits of using PCM in heat shield, are discussed.

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1. INTRODUCTION

1.1. BACKGROUND

One of the biggest issues in designing and building the Entry Vehicles is high temperature caused by planet atmosphere resistance in entry phase. Even though a typical option is using an ablator, it is desired to use Phase Change Material (PCM) in order to overcome the high heat flux during atmospheric entry phase and save some energy for future use. PCMs can be used to absorb, store, and convert the thermal energy into the electrical power for the vehicle.

PCMs are the kind of materials that have high heats of fusion; as a result, they can absorb a lot of energy during melting while temperature remains constant during this phenomenon.

To approach the goals for this project Thermal Desktop was used to make the model and Sinda/Fluint to simulate the internal heat transfer. The ideal goal of this project is to conceptualize the heat shield, which not only can shield the Entry Vehicle but store energy as well. As PCM absorbs the thermal energy, the temperature begins to rise to its melting point. Once melting has started in PCM, the temperature stays constant during the phase change. This occurs because the thermal energy from the heat source is being used to change the phase of the material from solid to liquid or vice versa. The PCM layer closest to the incident heat load will melt first and then the process will propagate through all of the initially solid PCMs. Once the PCM is in its liquid phase, natural convection will be generated due to buoyancy effect. Buoyancy effect is the results of the spacecraft deceleration during entry phase (g-force). As heat is conducted

into the liquid PCM, the hotter (denser) liquid PCM will be replaced by the cooler (less dense) liquid PCM via the “buoyancy effect” [4]. Figure 1 demonstrates the buoyancy effect of natural convection and melting propagation through the PCM [4].

Figure 1 a, b, c, “Buoyancy Effect” of Natural Convection and Melting propagation through the PCM

In this preliminary study, for the first step, two models of PCM-based cooling devices were simulated as benchmarks for validating the simulation with Sinda/Fluint. The first model is an experimental test unit (benchmark-1), containing an energy storage tank, different types of Bronze finned tube, phase change material (water), pumps, and measurement devices. Heat transferred from PCM to the cold flowing fluid inside the tube causes solidification of PCM. Second model is a container built of Aluminum fins and the PCM used in this model is Aristowax (benchmark-2). On the top side of the container, a convective cooling is applied and to the bottom side a study heat load is applied. The next step will be design of the heat shield and the thermal management system to protect the equipment in entry phase by use of PCMs.

1.2. SINDA/FLUINT - THERMAL DESKTOP

The analytical tools application has been limited for modeling multi-phase transport devices. Many users and engineers were used to demonstrate basic methods like spreadsheets and hand calculations even though it makes them very limited to specific designs. Sinda/Fluint, as the NASA-standard heat transfer and fluid flow analyzer, which is even used by Lockheed Martin, is the most multi-purpose analyzer for thermodynamic and heat transfer modeling. Sinda/Fluint is the only code available with special tools for dealing with capillarity and space and launch environments. This feature makes it applicable for start-up transient to top-level integration studies. Thermal Desktop as the model maker for Sinda/Fluint has capabilities of creating model with the Autodesk drafting software, AutoCAD. Thermal Desktop allows the users to easily and quickly build, analyze, and post process the thermal models using Sinda/Fluint. Thermal Desktop has the options for users to make their model with structure or unstructured grids depending on the complexity of the model. It also has the features of inputs based on time variables that allow the users to make more realistic simulation [7].

2. THEORY

PCM is a type of material with the ability to store heat during phase change at certain temperature. In PCMs, energy storage is formed usually between the solid and liquid states. Heat capacity that has been modeled in traditional Computational Fluid Dynamics (CFD) code is represented by specific heat (C_p). Equation 1 represents the latent heat, heat capacity for below melting point, and heat capacity for above melting point. This equation was solved numerically with Sinda/Fluint. Q is the absorbed heat, m , mass of PCM, a_m , fraction of melt, Δh_m , heat of fusion (latent heat), T_1 , initial temperature, T_2 , final temperature, T_m , melting temperature, $C_{p,s}$, specific heat of solid phase (above melting point) , and $C_{p,l}$ specific heat of liquid phase (below melting point).

$$Q = ma_m\Delta h_m + \int_{T_1}^{T_m} m c_{p,s}dT + \int_{T_m}^{T_2} m c_{p,l}dT \quad (1)$$

For pure PCM the phase change occurs at a constant temperature. To model, this would require an infinite specific heat. By allowing the latent heat absorption to artificially occur over a small finite temperature range, an artificial specific heat can be calculated and used [11].

3. MODEL SETUP

3.1. LITERATURE REVIEW / BENCHMARK CASE

The goal of the literature review was to find similar work done in the area of the new study. In order to validate new methods of solving the problems, simulating the similar tested methods partially or fully is necessary to obtain the same or close results. That being said, a few papers were reviewed in the areas of using phase change materials and thermal energy storage systems. Finally, two of the closest works done in those areas, which included experiments, simulations, or both, were found and were used as benchmarks for this research [1 and 2].

The Thermal Desktop was used to build the thermal models and Sinda/Fluint to simulate the heat transferred in the systems with the actual geometry and materials used in the models to have the closest simulation possible.

For the first case, a Thermal Energy Storage System was simulated and the results were compared. Compared results contain the amount of ice built around the tube and fins, and furthermore the amount of energy stored in the system. In the second case, a Thermal Management System, which is a Temperature Control System, was simulated and the temperature rate in the system as a result was compared. Simulated cases and compared results validated the heat transfer code and provided the optimal ways of approaching the design problem.

3.2. CASE-1: THERMAL ENERGY STORAGE UNIT

The first paper that is selected for the benchmark for this project, Ref.1, suggests experimental and numerical simulation of heat transfer based on phase change material for a thermal energy storage system. In this paper, authors had studied and calculated the thermal energy stored in the system and simulated the same process through the numerical model. The system works like a thermal energy sink that by losing energy provides the capacity of absorbing thermal energy for controlling the environment temperature. This paper is selected to validate the process of simulating the stored thermal energy in the final design. Even though the material and the temperature range is very different, the concept of the phenomenon is the same.

Using phase change material as latent heat thermal energy storage for buildings is one of the effective ways of saving and reusing energy for peak electrical load. One way is to use the Thermal Energy Storage Unit (TESU), which consists of the annular shell around finned tube filled with PCM. Fins are used to increase the heat transfer surface, which in turn increases the thermal energy storage [1].

In the design process, once the melting or solidification temperature of used PCM is known, the operating conditions and the storage configuration can be predicted. In such a system, heat transfer fluid (HTF) flowing inside the tube is used to transfer the thermal energy to or from phase change material.

The simulated model consists of an energy storage tank, different types of bronze finned tube, phase change material, pumps and measurement devices. PCM used in this model is water at a temperature of 0.3°C. Ethyl Alcohol as a coolant is flowing inside the

tube at a temperature range of -20°C to -10°C . Heat transferred from PCM to the current inside the tube causes solidification of PCM.

Figure 2 displays a schematic representation of the physical model [1]. PCM is surrounding the finned tube of inner radius r_o and outer radius r_{inf} . The tube wall inside and outside radius are respectively r_i and r_o . T_{in} is the temperature and $\dot{m}$ is the mass flow rate of heat transfer fluid flowing inside the tube. Initial temperature of the system is T_i higher than T_m mushy phase temperature.

Figure 2 A schematic of the thermal energy storage system with finned tube

3.2.1. NUMERICAL METHOD

In this section, some of the equations that had been used by the authors of the benchmark-1 to simulate the stored thermal energy in the system numerically are provided. Some of these equations had been used to calculate the Reynolds number and mass transfer rate to be imported into the created model by Thermal Desktop. Some of them were used to calculate dimensionless parameters for the result comparison. In numerical simulation, natural convection effects had been neglected. A complete list of equations and information about the numerical equations is provided in Ref.1.

Regarding Ref.1, at a time step, the changes in the stored energy of the PCM and finned tube must be equal to the total energy supplied by the heat transfer fluid as following:

$$\int_0^\tau \frac{\pi}{4} Pe_f C_f (\theta_{b,out} + 1) d\tau = \int_0^L \int_{R_i}^{R_{out}} 2\pi R (H - H_i) dR dX \quad (2)$$

$$R = \frac{r}{D}, \quad X = \frac{x}{D}, \quad \tau = \frac{\alpha_f t}{D^2}, \quad \theta = \frac{T - T_m}{T_m - T_{in}},$$

$$Re_f = 4 \frac{\dot{m}}{\pi D \mu_f}, \quad Pr_f = \frac{\nu_f}{\alpha_f}, \quad Pe_f = Re_f Pr_f, \quad C = \frac{C^0}{\rho_1 c_1}, \quad S = \frac{S^0}{\rho_1 c_1 (T_m - T_{in})}$$

where $H = C.T + S$, total enthalpy at the control volume [1], C_f is specific heat, C^0 , heat capacity, D inside diameter of the circular pipe, and $\dot{m}$, mass flow rate. Pe_f is the fluid peclet number, Pr_f , fluid Prenatal number, r , radial co-ordinate, R , dimensionless radial direction, and Re_f , fluid Reynolds number. S^0 is source term, S , dimensionless source term, T , temperature, T_{in} , initial temperature, T_m , melting temperature, and t , time. X is dimensionless axial direction, x , radial co-ordinate, α_f , thermal diffusivity of transfer

fluid, θ , dimensionless temperature, ν_f , kinematic viscosity of the fluid, μ_f , dynamic viscosity of the fluid, ρ_1 , density of PCM, and τ dimensionless time.

The left side of Eq. 2 represents the thermal energy stored in the PCM and fins and the right side represents the thermal energy supplied to the heat transfer fluid. The following equations are used to reduce the number of parameters in Eq.2 [1]. Equation 3 in particular was used to calculate the mass transfer rate for the simulation with Sinda/Fluint.

$$\dot{m} = \frac{1}{4} \cdot \pi D \mu_f \cdot Re_f \quad (3)$$

3.2.2. SIMULATION

In Thermal Desktop, the model is created in AutoCAD and will be imported to the Thermal system. For this specific simulation, the model was created in 3D platform. As Figure 2 displays, a schematic representation of the physical model includes the Bronze made finned tube and phase change materials surrounding it. The 3D model was formed based on the 2D surfaces with constant thickness. Thermal Desktop provides the optimal conditions for having the combination of 2D and 3D surfaces. In addition, because the model is symmetric, the simulation utilizes half of the actual model.

Based on the benchmark-1 dimensions, Table 1, lines and surfaces were formed to have the geometry exactly like the geometry in the benchmark-1 (Figure 3) [8]. Thermal Desktop has different options in order to generate grids in the model, structured and unstructured. For this model, the structured grid was selected to have a fast and simple simulation. In order to have the reasonable node distribution, certain node numbers were selected along the width and depth of the model to make the grid fine enough for capturing the physics of the problem. Furthermore, to increase the accuracy of the numerical solution, the incremental distance between nodes was decreased as they approached the tube surface in Y-axis direction (Figure 4). In X-axis direction, node distribution was uniform with equal grid distance.

Table 1 - Details of the thermal energy storage unit

r_{inf} (mm)	r_o (mm)	r_i (mm)	T_{in} (°C)	T_i (°C)
270	15	10	-10	0.3
t_{fin} (mm)	h_{fin} (mm)	d_{fins} (mm)	T_m (°C)	$\dot{m}$ (kg/sec)
3	27	65	0.0	0.0844
h_{tank} (mm)	W_{tank} (mm)	l_{tank} (mm)	l_{tube} (mm)	Re
570	420	500	480	500

Table 1 contains the initial and boundary conditions in addition to the model dimension based on the benchmark-1 information.

In order to identify each part of the model, properties of materials were applied separately to each section. Table 2 indicates the material properties of bronze (used in tube and fins) and water (used as PCM) [8].

Table 2 - Properties of materials used in the case-1 simulation

<i>Property</i>	<i>Bronze</i>	<i>Water</i>
Density-solid, kg/m ³	8820	897
Density-liquid, kg/m ³	---	998.23
Specific heat-solid, J/kg-K	435	210000
Specific heat-liquid, J/kg-K	---	4181.9
Heat of fusion, kJ/kg	386.9	333.55
Melt-temperature, °C	660.37	0.00
Conductivity-solid, W/m-K	71.9	0.609

As shown in Figure 3, dark blue area is water (PCM), gray surface is the tube, and orange circular shapes are the fins. Figure 4 demonstrates the node distribution among the model in both bronze tube and fins and PCM. Green area is water, dark blue area is the bronze tube, and red lines indicate the fins.

Figure 3 Model of thermal energy storage system

Figure 4 Grids for the model of thermal energy storage system

3.2.3. RESULTS

The following figures show the contour of temperature distribution after one and two hours of starting of the experiment respectively. Time lines were selected particularly to match the time lines in the referenced paper. Figure 5 displays temperature distribution contours around the tube and fins inside the PCM after one hour of experiment. Green areas are the area with the temperature of below 0.0°C , which is the ice built temperature. As shown, the temperature of the tube is much below the -0.1°C and it is about -10°C , about the temperature of Ethyl-alcohol flowing inside the tube. At the time of one hour, the maximum temperature in PCM is about 0.3°C and the minimum -0.7°C .

Figure 6 displays temperature distribution contours around the tube and fins surrounded by PCM after two hours of experiment. Green areas like in Figure 5 are the area with the temperature of below 0.0°C . As displayed, solidification had increased to the larger margin as it was expected. At the time of two hours, the maximum temperature in the PCM is about 0.3°C and the minimum -1.35°C . As shown in Figure 7 and Figure 8, the schematic 3D profiles depicted the temperature propagation within PCM. X-axis indicates the height (cm) of the PCM from the layer next to tube to the top of the tank. Y-axis and Z-axis indicate the temperature ($^{\circ}\text{C}$) and simulation time (sec) respectively. As shown in Figure 7, which indicates the temperature distribution within the layers of the PCM next to the fin, there are sharp profile drops due to imminence of PCM layer to the fin. Figure 8 displays the temperature distribution within the PCM between two fins. The results indicate that temperature drop is much smoother in the middle of the fins rather than the layers near the fin.

Figure 5 Demonstration of propagation of the freezing temperature after 1 hour

Figure 6 Demonstration of propagation of the freezing temperature after 2 hours

Figure 7 Schematic 3D figure of temperature distribution inside PCM from tube surface next to a fin to the top side of the tank

Figure 8 Schematic 3D figure of temperature distribution inside PCM from tube surface in middle of two fins to the top side of the tank

3.2.4. DISCUSSION AND BENCHMARK COMPARISON

In this section, results from Sinda/Fluint are compared to the benchmark-1. At each time, both experimental and simulated results are put next to each other for comparison. Therefore, Figure 9 displays the experimented simulation from the benchmark-1 right next to the Sinda/Fluint simulation for running time of two hours. PCM solidification around the tube and fins is clearly seen. The amount of thermal energy stored in the system can be indicated based on the amount of ice around the tube. At this point, the amount of ice around the finned tube in Sinda/Fluint simulation is equivalent to the same form the benchmark-1 (Figure 10). Figure 10 indicates the comparison of the results obtained by simulated model with Sinda/Fluint and the results from the benchmark-1.

Figure 9 The solidification of finned tube after 2 hour

As shown, the amount of ice had increased after two hours of simulation. The blue line indicates the solidification results after one hour and the red line for two hours.

Figure 10 Results of solidification front in thermal energy storage system

3.3. CASE-2: THERMAL MANAGEMENT SYSTEM

According to the referenced paper, Ref.2, typical temperature range in many Thermal Management Systems (TMS) is from $-15\text{ }^{\circ}\text{C}$ to $190\text{ }^{\circ}\text{C}$. For this range of temperature, the good latent heat values tend to range between 150 kJ/kg to 250 kJ/kg . This study suggested an experimental simulation of heat transfer based on PCM for a TMS. The simulated model is a container built of Aluminum fins and the PCM used in this model is Aristowax. On the top side of the container, a convective cooling is considered, $h_c = 50\text{ W/m}^2\text{-}^{\circ}\text{C}$, and to the bottom side a study heat load is applied, $q_{in} = 20\text{ kW/m}^2$. Figure 11 illustrates the schematic figure of a PCM-based cooling arrangement [2].

Using the simulated model as a benchmark to model the same device and comparing the results of the same application validates the numerical simulator. In this case, Sinda/Fluint has been used to as a numerical code to simulate the heat transfer within the PCM.

Figure 11 A simple schematic of a PCM-based cooling arrangement

3.3.1. ANALYTICAL METHOD

The benchmark used to validate the numerical simulation with the results is presented in Ref. 2. Because PCM undergoes a phase change from solid to liquid when it reaches the melting point by absorbing enough heat, buoyancy effects can control the melting front position movement of the PCM. In the benchmark-2, these types of behavior were explained with Navier-Stokes equations, and the buoyancy effects are presented by the Boussinesque approximation. In addition, the movement of solid-melt front is tracked by the enthalpy methods.

3.3.2. SIMULATION

The finite element model created by Thermal Desktop and based on the parameter provided in Table 3 was solved with Sinda/Fluint. For this specific simulation, the model was created in 2D platform. Figure 12 shows a typical cross-section view of the Model that includes the Aluminum fins and phase change materials [2]. Followed by the benchmark-2 dimensions, Table 3, lines and surfaces are formed to have the geometry exactly like the geometry in the benchmark-2 (Figure 13) [2]. Sections A and B in Figure 13 are included in the simulation to contain the fins and the PCMs.

Table 3 - Details of thermal management system

$t_{fin}(cm)$	$t_{PCM}(cm)$	$h_h(cm)$	$h_{PCM}(cm)$	$h_t(cm)$
0.4	1.357	0.3	12.1	0.3
$m_{Al}(kg)$	$m_{PCM}(kg)$	$m_{total}(kg)$	$q_{in}(W/m^2)$	$h_c(W/m^2-^{\circ}C)$
1.31	1.09	2.40	20000	50

Figure 12 A typical cross-section view of the Model

Figure 13 Details of the geometry and boundary conditions for the 2D simulation

In order to identify each part of the model, properties of materials were applied separately to each section as Table 4 indicates the materials properties for Aluminum and Aristowax 165 [2].

Table 4 - Properties of materials used in the case-2 simulation

<i>Property</i>	<i>Aluminum</i>	<i>Aristowax 165</i>
Density-solid, kg/m ³	2698.9	931
Density-liquid, kg/m ³	---	770
Specific heat-solid, kJ/kg-K	0.9	2.093
Heat of fusion, kJ/kg	386.9	186.1
Melt-temperature, °C	660.37	70.0
Conductivity-solid, W/m-K	210	0.15

Thermal Desktop can generate structured and unstructured grids in the model. For this model, the structured grid was selected to have a fast and simple simulation. Nodes are placed in a uniform format to cover the entire surfaces with the equal distance. Some of the boundary nodes in Aluminum fins and all the nodes in PCMs are merged respectively to their pair nodes to help the solver to converge faster. Figure 14 demonstrates the node distribution among the model in both Aluminum fins and PCMs. Green areas are the Aluminum fins, and cyan area is the PCMs. In the last part, Heat flux of $q_{in} = 20 \text{ kW/m}^2$ was applied to the model. Red dots displayed in the bottom part of Figure 14 are the nodes with applied heat flux to them.

Figure 14 Grids and nodes generated in Thermal Desktop for the model

3.3.3. RESULTS

The following figures show the contour of temperature distribution at different times. On the left hand side, the figure demonstrates the whole model with Aluminum fins surrounding the PCMs, and on the right hand side, more details of propagation of the temperature in PCM are shown. Timelines were selected particularly to match the time lines in the benchmark-2. On the right hand side and left hand side of the figure, indicated color temperature might be slightly different because the aluminum fins on the right hand side are not shown.

Figure 15 indicates the results at the time of 592 seconds. At this time, the maximum temperature in the model was about 77 °C and the minimum 44 °C. PCM was just starting to melt at the touching points with Aluminum fins. The light orange color indicates the temperature of 70 °C, melting temperature of Aristowax, distributed from the bottom of the figure to the sides, showing how PCM started to melt and how heat flux moves through the material (right hand side).

Figure 15 Demonstration of propagation of the temperature at 592 sec

Figure 16 indicates the results at the time of 992 seconds. At this time, the maximum temperature in the model was about 94 °C and the minimum 64 °C. As time went by, more PCM is melted and the temperature of the whole materials is increased. As shown on the right hand side figure, layers of PCM close to the fins are melted.

Figure 16 Demonstration of propagation of the temperature at 992 sec

Figure 17 and Figure 18 indicate the results at the time of 1392 seconds. At this time, the maximum temperature in the model was about 113 °C and the minimum 69 °C. Results show the temperature of PCMs standing close to 70 °C, melting point, and perhaps by raising the temperature the only thing that would happen was increasing the temperature in the whole system. By this time, PCM has been melted already and the system had reached the predicted capacity of absorbing energy.

Figure 17 Demonstration of propagation of the temperature at 1392 sec into the model

Figure 18 Demonstration of propagation of the temperature at 1392 sec into PCM

3.3.4. DISCUSSION AND BENCHMARK COMPARISON

In this section, simulated results from Sinda/Fluint are compared to the experimental data from the benchmark-2. As shown in Figure 19, at heat source, $y = 0$ cm, first comparison point, the temperature started at 20 °C and during the simulation time, 1600 seconds, temperature increased to about 120 °C. As the profile shows, temperature in benchmark-2 and simulated model both follows the same increasing slopes aside with a minor difference, about 5-10 %, at the beginning and converge at the end. The second point was at midpoint of the model, $y=6.35$ cm, the lowest black dash line in the figure. This point was selected to show the temperature change inside PCMs. Benchmark-2 results show temperature increase from 20 °C, going to about 60 °C, staying almost steady for about 600 seconds then increased to the melting point, 70 °C. Simulated results are a bit different even though the slope of rising temperature is the same. After 600 seconds of applying thermal energy to the system, PCMs started to melt and temperature stayed steady from melting point to the end of the simulations. The last point is at heat sink, $y = 12.7$ cm, at the top of the model. At this point, benchmark-2 and Sinda/Fluint results are the same and they are following the same path. They are slightly different in the beginning but converging at the end. The reason is being investigated.

Figure 20 indicates the linear contour of melting temperature distribution at different times inside PCMs compared to the benchmark-2 model. As shown in Figure 15, Figure 16, and Figure 18, the same phenomenon happened in the simulated model with Sinda/Fluint.

Figure 19 Compared results between benchmark-2 and simulation

Figure 20 Demonstration of propagation of the melt-front into the PCM with time

3.4. CASE STUDY CONCLUSION

In the past sections, two cases that were studies based on experimental data of phase change materials were reviewed and models were numerically simulated by Sinda/Fluent. The goal was to find similar results in the area of the new study to validate the new method.

In case-1, a Thermal Energy Storage Unit was simulated and the results were compared to the results from referred benchmark, Ref.2. PCM solidified around the finned tube determined the correctness of the simulated model.

In case-2, a Thermal Management System was simulated. Benchmark-2 results and simulated results are close to each other. They were slightly different in the beginning but converged to the end. Nevertheless, the very low percentage of error, about 5-10 %, is acceptable.

4. APPLICATION

4.1. BACKGROUND OF THE PROBLEM

Thermal Protection System (TPS) is one of the main issues in designing and building the Entry Vehicles. Dealing with high temperature caused by planet atmosphere resistance in entry phase make designing the TPS complicated. A typical option is ablator but limitation of using it forces scientists to look for other ways in order to increase the efficiency and reusability of the vehicle's components. One option is using PCM in order to shield the Entry Vehicle during entry and save some energy for future use. PCMs can be used to absorb, store, and convert the thermal energy into electrical power for the vehicle. It can maintain the extended temperature of the heat shield below melting points. Furthermore, PCMs can be used as a main component of vehicle thermal management systems. For instance, if the probe lands on a cold planet, stored energy in PCM can be utilized to compensate the thermal energy needed for the vehicle. In a real case design, heat loop pipes as advanced heat pipes enable transferring the heat from the warm side - PCM section - to the cold side of the spacecraft. In addition, Thermal energy stored in PCM can be converted to electricity for internal spacecraft usage. Furthermore, one disadvantage in TPS using ablator is failure of a single unit (tile), which would cause failure of the entire system; however, in PCM there is no single failure point.

In order to design a TPS based on phase change material, Mars Pathfinder (MPF) explorer was selected as an example of an entry probe, and its mission trajectory to Mars was used to obtain the heat load applied on the surface of the vehicle. Figure 21 displays the temperature distribution around the MPF during the entry phase [6]. To simplifying

the problem, instead of analyzing the whole body, stagnation point as a critical point (shown in Figure 24) was used for simulation and analysis. Red arrows depict heat load distribution in Figure 22.

Some of the main assumptions for simplifying the design are the following:

- 1) Applied heat assumed to be uniform all over the stagnation point area. Therefore, a small area around the stagnation point was modeled with the straight shape and width of one unit. This area is about 9.2 cm^2 .
- 2) Angle of attack assumed to be 0° and according to Ref.4, 100% of the heat flux is incident at the stagnation point.
- 3) The heat shield assumed to be insulated from the inner components of the spacecraft.
- 4) Conductivity of PCM will decrease when phase change happens from solid to liquid but it can be compensated by g-force applied during entry.
- 5) Dissipation of heat from the heat shield to space or Mars atmosphere is neglected.

Figure 21 A schematic of temperature distribution around the MPF

Figure 22 A schematic of the heat load distribution over the MPF

4.2. MATERIAL SELECTION

There are certain qualities that the selected PCM should have in order to act as an optimal material chosen for the Thermal Protection System and Thermal Management System. Density, heat of fusion, heat capacity, and melting point are the important parameter used to select the right material. Depending on the goal of the design, high and low temperature PCMs will be selected. For example, if the design requires absorption of huge amount of thermal energy like designing the TPS, high heat PCMs will be selected. Usually, high heat phase change materials have a high heat of fusion and a high melting point that enable them to be able to absorb and store enormous amounts of thermal energy for future system usage whether to dissipate to the atmosphere or convert for internal usage. On the other hand, if the design desired is to manage the thermal condition of an environment, thermal management systems, low heat materials will be selected. Table 5 contains the potential phase change materials for the design concepts [9].

Table 5 – Potential materials of high and low Temperature PCMs

High Temperature PCMs		Low Temperature PCMs	
<i>Material</i>	<i>Melting point °C</i>	<i>Material</i>	<i>Melting point °C</i>
LiF	848.2	AlBr ₃	97.5
LiBr ₃	552	GaI ₃	212
CuCl	430	TaCl ₅	216
CsNO ₃	414	BiBr ₃	218

In particular, Lithium Fluoride (LiF) was selected for this conceptual design study because it satisfies requirement of the high heat capacity and high temperature with melting point of 848.2°C. Carbon-Carbon composite was selected for the probe outer skin and fins because of very high melting point of 3500 °C and availability of the material in the industry.

4.3. MODELING THE DESIGN

Thermal Desktop was selected to create the finite element model of the heat shield based on phase change materials to be simulated and analyzed the heating experience during the entry phase with Sinda/Fluint.

The designed heat shield consists of a Carbon-Carbon composite base for the outer skin of the probe, which encapsulated the PCM. Fins, which are assumed to be attached directly perpendicular to the outer skin, are made of Carbon-Carbon to improve the heat transfer through the PCM. Since thermal conductivity of the fins are much higher than PCM, thermal energy routs into the latter portion of the PCM [9]. Table 6 indicates the dimensions and initial conditions of the model. Thickness of the fins, outer skin, and PCM are indicated respectively by t_{fin} , $t_{heat\ shield}$, t_{PCM} . $T_{outside}$, the initial outer skin temperature assumed for being in deep space, T_{in} , initial temperature condition, $q_{in-peak}$, peak heat load at stagnation point, d_1 , distance between fins for the first design assumption, and d_2 is the distance between fins for the second design assumption. The total length of the finite element model is 5 cm, the PCM and fin lengths are 4.7 cm and the outer skin height is 0.3 cm. Material properties of selected materials for this conceptual design are listed in Table 7 [8].

Table 6 - Details of the initial designed model

$t_{fin}(cm)$	$t_{heat\ shield}(cm)$	$t_{PCM}(cm)$	$d_1\ fin(cm)$
0.2	0.3	4.7	10
$T_{outside}(^{\circ}C)$	$T_{initial}(^{\circ}C)$	$q_{in-peak}(W/cm^2)$	$d_2\ fin(cm)$
-150	0	119	5

Table 7 - Properties of materials used in the design

<i>Property</i>	<i>Carbon-Carbon</i>	<i>LiF</i>
Density-solid, kg/m ³	1800	2640
Density-liquid, kg/m ³	---	2640
Specific heat-solid, J/kg-K	2102.96	1548.08
Heat of fusion, kJ/kg	---	1044.4
Melt-temperature, °C	3500	848.4
Conductivity-solid, W/m-K	250	11.3

Figure 23 displays a created 3D model of the Mars Pathfinder to indicate the fins and PCM location and shapes. The outer skin of the MPF and fins is assumed to be made of Carbon-Carbon composite. In order to have a clear display of the mentioned components, showing the other parts of spacecraft is neglected.

Figure 23 Schematic 3D model of the MPF

Figure 24 shows a schematic drawing of the MPF geometry to specify dimensions, location of stagnation point (red square), and heat load distribution over the outer skin. The blue area indicates the approximate width of the PCM in order to compare the thickness of the designed heat shield to the whole spacecraft width. Mars Pathfinder has an initial depth of 140 cm, and the thickness of the primary designed heat shield, including outer skin and PCM, is about 5 cm.

Figure 24 A schematic of the geometry, dimensions and stagnation point location

Based on Ref. 5, the heat rate on the stagnation point for Mars pathfinder follows the Gaussian curve with the peak point of 119 W/cm^2 at 64 seconds of entry phase. In order to simulate the heat load over the spacecraft, as shown in Figure 25, the heat rate as a function of entry time was applied to the created model, designed heat shield. MATLAB is used to generate the solution for Gaussian equation and generated heat loads over the time steps were imported as a timetable into the Thermal Desktop.

Figure 25 Mars Pathfinder Heat rate and total heat load

The following steps were required in order to create the primary design model in Thermal Desktop:

- 1) Based on Table 6, assumptions for the primary design, 2D geometry was created with the unit constant depth to generate the 3D simulation.
- 2) Materials properties were applied to each components regarding Table 7.
- 3) To create the optimal numerical model, finite element model, grids were generated with incremental distance increase.
- 4) Heat load was applied to the outer layer of the model based on generated heat rate via MATLAB code.

The final step is to use Sinda/Fluint solver as the analyzer to simulate the heating experience.

4.4. GRID GENERATING

Grid generating is one of the main steps toward making finite element model for numerical simulation. In order to increase the accuracy of the numerical solution, incremental distance between nodes in PCM and fins was decreased as they approached the skin surface in X-axis direction (Figure 26 and Figure 27). The distance increment applied to the generated grid is 105%. In Y-axis direction, node distribution was uniform with equal grid distance. Figure 27 indicates the location of the applied heat load on the outer layer of the skin in generated grid.

Figure 26 Grids generated in Thermal Desktop for the model

Figure 27 Grids generated in Thermal Desktop for the model with fin

4.5. VISUALIZATION

The next step after creating the model and generating the grinds is to visualize the results. The following figures (Figure 28, Figure 29, and Figure 30) demonstrate the propagation of the temperature into PCM at the end of the flight. Entire entry duration was 160 second. Heating the heat shield is simulated for three different cases: 1) the initial simulation for the model with no perpendicular fins, 2) model with fin distance of 10 cm, and 3) model with fin distance of 5 cm.

In Figure 28, heat distribution is demonstrated into PCM for case (1), and in addition to the temperature propagation, the location of phase changing is indicated. The maximum temperature is 852.3°C, and the minimum temperature is about 0.0°C.

Figure 28 Demonstration of propagation of the temperature into PCM for model with no fin

Figure 29 displays the temperature distribution for case (2), fin distance of 10cm. As it shows, the fins improved the heat transfer into the PCM, overall temperature of the model decreased and melting front position moved further into the PCM. Based on the numerical results, location of the phase changing is indicated in Figure 29; even though, the temperature shown in the figure is lower than melting temperature of LiF. Figure 29 shows the temperature distribution at the time of 160 second. In the discussion section, schematic 3D temperature distribution graphs signify the phase changing location in Figure 28, Figure 29, and Figure 30. The maximum temperature decreased to 567.7°C, and the minimum temperature is about 0.0°C.

Figure 29 Demonstration of propagation of the temperature into PCM distance between fins 10 cm

Figure 30 shows the temperature propagation for the simulated model with fin distance of 5cm. In general, effects of reducing the fins distance in the model in addition to increase the heat transfer rate along the PCM, decrease the weight of the heat shield. Because Carbon-Carbon has lower density than LiF, by substituting and amount of PCM with the fins, weight if the heat shield will decrease.

Figure 30 Demonstration of propagation of the temperature into PCM distance between fins 5 cm

5. RESULTS AND DISCUSSION

Sinda/Fluint as the heat transfer simulator was run for three different primary design models mentioned in section 4.5. The results of the simulation were imported into ExcelPlotter to plot the temperature distribution into the PCM and over the outer skin.

According to the results of simulation, for the 160 seconds of entry phase duration, caused about 130 seconds of heating with the heat rate profile displayed in Figure 25 and with a peak heat rate of 119 W/cm^2 at the stagnation point, the heat shield sustained the total applied heat. In the below figures, the horizontal lines stand for the phase changing process. During phase change, the temperature of the PCM remains constant and that causes the horizontal lines in the temperature distribution profiles. In addition, because of the affects of natural convection and phase change, the temperature of the outer skin and PCM begin to decrease once the peak heating phase ends.

Figure 31, Figure 32, and Figure 37 demonstrate case (1) simulation. For this case, the outer skin of the heat shield reached the maximum temperature of 1491°C and the outer layer of PCM next to the skin reached the maximum temperature of 1484°C at 79 seconds of the entry phase. Figure 31 demonstrates the temperature distribution profile of the outer and at distances of 1.5 mm into the skin, midpoint. Figure 32 depicts the temperature distribution profile at various depths within PCM. The melting front position of the PCM propagated through 1.64 mm of its length, 4.64 mm from the outer skin, which is indicated by the horizontal line. Regarding the maximum temperature reached by the outer skin of the heat shield, it is required to select a material that will be able to sustain extreme conditions, specifically high temperatures and remain in the mechanical property conditions. Because

Carbon-Carbon composite has high melting temperatures of 3500 °C, it is suitable for these conditions.

Figure 33, Figure 32, and Figure 38 demonstrate case (2) simulation. For this case, the outer skin of the heat shield reached the maximum temperature of 1280 °C and the outer layer of PCM next to the skin reached the maximum temperature of 1044 °C at 80 seconds of the entry phase. The melting front position of the PCM propagated through 1.04 mm of its length, which is indicated in Figure 34. Based on the new results, with the same amount of heat load, outer skin maximum temperature decreased and the melting front position of PCM moved toward the skin. This finding signifies the improvement of the heat transfer into the heat shield and increases the absorption rate of thermal energy.

Figure 35, Figure 36, and Figure 38 demonstrate case (3) simulation. For this case, the outer skin of the heat shield reached the maximum temperature of 1029 °C and the outer layer of PCM next to the skin reached the maximum temperature of 921 °C at 77 seconds of the entry phase. The melting front position of the PCM propagated through 0.43 mm of its length, which is indicated in Figure 36. Based on the results of this case, with the same amount of heat load as case (1) and (2), outer skin maximum temperature decreased and the melting front position of PCM moved toward the skin, almost 0.43 mm from the skin. As shown in the results, PCM essentially slows down the increase in the outer skin temperature due to the phase change process.

Regarding the results and the above discussion, case (3) has the better performance compared to the other cases. In this case, the melting front position is close to the skin, at 0.43 mm of PCM length, and the maximum PCM temperature, 921 °C, does not approach the LiF boiling point of 1676 °C. Thermal energy distributed almost into all layers of PCM.

Figure 31 Stagnation point temperature vs. entry time for the case (I)

Figure 32 Temperature distribution at different depth into PCM for the case (I)

Figure 33 Stagnation point temperature vs. entry time for the case (2)

Figure 34 Temperature distribution at different depth into PCM for the case (2)

Figure 35 Stagnation point temperature vs. entry time for the case (3)

Figure 36 Temperature distribution at different depth into PCM for the case (3)

The following figures (Figure 37, Figure 38, and Figure 39) demonstrate the 3D temperature distribution within PCM. X-axis indicates the depth (mm) of the PCM from the layer next to skin to its last layer. Y-axis and Z-axis indicate the temperature ($^{\circ}\text{C}$) and entry time (sec) respectively. As shown in Figure 37, which indicates case(1) results, temperature profiles before melting front position had risen to the peak point at 79 seconds, and then, they had slowed down to the temperature that is relatively in balance with next layers. For the layers after melting front position, temperature had risen and this increase had slowed down within the PCM until there is no temperature increase at 25.94 mm of its length. Almost the same procedure had happened for the next cases. For case (2), results shown in Figure 38, peak temperature occurred at 80 second, and the front line of temperature increase within PCM was at 25.94 mm of its length, with the same depth of case (1). Results of case (3) displayed in Figure 39. The peak temperature occurred at 77 second; however, interestingly enough, slowing down of heat transfer flowed to the last layer of the PCM.

Figure 37 3D Temperature distribution at different depth into PCM for the case (1)

Figure 38 3D Temperature distribution at different depth into PCM for the case (2)

Figure 39 3D Temperature distribution at different depth into PCM for the case (3)

6. OPTIMIZATION

One of the main concerns in designing the heat shield is the weight challenge. The typical ablator initially weight approximately around 140 kg to 160 kg, according to Ref.12. Calculated weight of the heat shield for case (3) design is about 560 kg because of having less PCM and more fins (Calculated weight of the heat shield for case (2) design is about 619 kg). The weight of the heat shield based on PCM is about 4 times of the ablator based. In this case, the design should go through the optimization process in order to come up with the reasonable weight compare to the existing ablator based heat shields. One way of optimizing is to reduce the thickness of PCM in places that absorb a small amount of thermal energy. As discussed for case (3) in Sec.5, even though thermal energy distributed all over the PCM, more than half of PCM remained at about initial condition without significant increase of temperature. As mentioned before, the main goal of using PCM in designing the heat shield is to absorb thermal energy and store or convert it to electricity. By that said, there is no reason to have huge amount of PCM without considerably temperature increase. Furthermore, weights of the spacecraft components are very essential to be as low as possible because any extra weight amplifies unnecessary expenses. Regarding the weight optimization, thickness of PCM and respectively length of the fins decreased to about 20% of the primary design. Results in the following figures (Figure 40, Figure 41, Figure 42, and Figure 43) indicate the satisfactory of the final optimization. In this case, weight of the heat shield decreased to 96 kg, comparable with the weight of the Ablator.

Figure 40 shows the temperature propagation for the optimized model. The maximum temperature is 872.7°C, and the minimum temperature is about 735°C. That shows the complete thermal energy distribution within the PCM layers. Total Energy stored in PCM for this case was about 33592.6 J (33.593 kJ, 205.416 BTU).

Figure 40 Demonstration of propagation of the temperature into PCM distance between fins 5 cm for optimized design

Figure 41, Figure 42, and Figure 43 demonstrate the results for an optimized model. In this case, the outer skin of the heat shield reached the maximum temperature of 1340 °C and the outer layer of PCM next to the skin reached the maximum temperature of 1174 °C at 81 seconds of the entry phase. Figure 42 depicts the temperature

distribution profile at various depths within PCM. The melting front position of the PCM propagated through 1.81 mm of its length, which is indicated by the horizontal line.

Figure 41 Stagnation point temperature vs. entry time for the model with fins distance of 5 cm for optimized design

The following figure demonstrates the 3D temperature distribution within PCM. As shown in Figure 43, which indicates optimized model results, temperature profiles shows the peak point at 81 seconds and the lowest temperature of 735 °C. The melting front position is at 1.81 mm inside of PCM.

Figure 42 Temperature distribution at different depth into PCM for the model with fins distance of 5 cm for optimized design

Figure 43 3D Temperature distribution at different depth into PCM for the model with fins distance of 5 cm for optimized design

7. CONCLUSIONS

The utilization of phase change materials in the heat shield of an atmospheric entry vehicle is considered here because of its ability to store energy for future use. The stored energy can be converted to the electricity for internal spacecraft use or/and internal thermal management system. The high latent heat of fusion of phase change materials, in this case Lithium Fluoride (LiF), enables it to absorb a huge amount of thermal energy during entry phase. For Mars Pathfinder explorer, the peak heat load at stagnation point is 119 W/cm^2 at 64 seconds of the entry phase. As the atmospheric entry had caused the heat load on the outer skin of the spacecraft, PCM had absorbed the heat and melted to the certain layers. The maximum propagation of the melting front position was at 1.81 mm. The total energy absorbed by the model was 33592.6 J (33.593 kJ). As mentioned before, the simulated model is a small portion of the heat shield (the area of 9.4 cm^2); therefore, the total amount of energy absorbed by the heat shield exceeds much higher than calculates quantity (heat shield front area is about 51095 cm^2). That being said, utilizing of PCM in the heat shield will enable future designers to use the enormous amount of absorbed thermal energy for TMS or convert it to electricity for internal spacecraft use.

For instance, if the heat shield just sustains 50% of the heat flux at stagnation point, the amount of energy absorbed by the heat shield will be around 91.3 MJ. This amount of energy is equivalent to 25.36 kWh. Specific energy density of the typical Lithium-ion battery is about 150-200 Wh/kg [16]. As a result, it can easily be calculated how much electricity can be stored or used from converting the stored thermal energy inside PCM.

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APPENDIX

APPENDIX A

MATLAB CODE FOR GRID DISTANCE INCREMENT

```
% Calculating the grid distance increment %
```

```
clc
```

```
clear
```

```
R = 1.07;
```

```
L = 1;
```

```
n = 40;
```

```
X(1)=0;
```

```
for j = 1:n;
```

```
    for i = 1:n;
```

```
         $p(i) = R^{(i-j)}$ ;
```

```
    end
```

```
     $I(j) = L / \text{sum}(p)$ ;
```

```
     $X(j+1) = I(j) + X(j)$ ;
```

```
     $X(j) = X(j+1)$ ;
```

```
end
```

```
A=X';
```

APPENDIX B

MATLAB CODE FOR CALCULATING THE HEAT RATE

```
% Calculating the heat rate based on Gaussian equation %  
  
clc  
  
clear  
  
A = 119;  
  
x0 = 64;  
  
y0 = x0;  
  
theta = 0;  
  
sigma_x = 17;  
  
sigma_y = sigma_x;  
  
a = (cos(theta)/sigma_x)^2 + (sin(theta)/sigma_y)^2;  
  
b = -sin(2*theta)/(sigma_x)^2 + sin(2*theta)/(sigma_y)^2 ;  
  
c = (sin(theta)/sigma_x)^2 + (cos(theta)/sigma_y)^2;  
  
[X, Y] = meshgrid(0:1:160, 0:1:160);  
  
Z = A*exp( - (a*(X-x0).^2 + b*(X-x0).*(Y-y0) + c*(Y-y0).^2)) ;  
  
plot(Z);  
  
A=Z(x0,:);
```