

Carbon foam impregnated with Phase Change Material (PCM) as a thermal barrier

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Introduction

Control of temperature and/or heat transfer is of crucial importance in numerous technical processes and natural occurrences. This can be achieved by using a thermal barrier to protect bounding surfaces of a system of interest. A thermal barrier utilizing solid liquid phase change material PCM is one of the passive thermal management techniques receiving great interest due to its inherent advantage of simplicity and reliability. Various geometric configurations have been considered for the phase change thermal management devices. The configuration of a PCM-filled rectangular cavity was considered for spacecraft thermal control [1]. The use of finned rectangular PCM-filled cavities was analyzed for thermal control of electronic equipment [2]. A numerical analysis was presented for thermal protection characteristics of a vertical rectangular cell filled with a solid-liquid PCM and air layer [3,4]. In this work, the buoyancy induced flows developed in both the air filled layer and the molten PCM zone were modeled as a two-dimensional laminar Newtonian flow. Although PCMs like paraffin waxes exhibit desirable properties as PCMs, they present a low thermal conductivity. This property reduces the thermal response of the thermal protection system and thereby may cause system overheating. Different techniques to offset this low thermal conductivity are studied mainly experimentally. These techniques include adding matrix structure [5], adding carbon fibers or carbon fiber brushes [6,7]. It was found that using these techniques has a great effect on enhancing the PCM thermal conductivity.

Melting and solidification of PCM inside porous matrix is a very complicated phenomenon. This is because there will be the solid phase of the porous matrix and the PCM which may be in solid, liquid or mushy state. Due to this complicated structure most of the works, which has been done in this field are based on volume averaging of the microscopic conservation equations to account for the complex interfacial structures of each constituents. This model offers the advantage that the entire domain can be treated as a single region governed by one set of conservation equations. In other words, the same equations can be used for the melt as for the fully solidified regions. Freezing and melting of water in saturated porous media contained in various enclosures have been studied experimentally and numerically by Weaver and Viskanta [8]. Their freezing experiments in rectangular cavity clearly showed the influence of natural convection on the solid/liquid interface shape and motion. Beckermann and Viskanta [9] combined numerical and experimental studies for solid/liquid phase change in porous media with natural convection in the molten region. Their model is based on

volume averaged transport equations, while phase change is assumed to occur over a small temperature range. Experiments are performed in a vertical, square enclosure using gallium and glass beads as the PCM and the porous matrix respectively.

In this work different carbon foams with different thermal conductivities and porosities filled with paraffin wax are introduced as a thermal barrier or carrier to protect bounding surfaces of a system of interest. The thermal characteristics of the thermal barrier are investigated experimentally and numerically in a simulated environment. The composite is introduced into a cylindrical enclosure while it experiences its heat from a heat source setting on the top of the enclosure. Due to the complexity of the porous media, the numerical simulation is performed using a volume averaging technique. Finite volume technique is used to discretize the heat diffusion equation and the enthalpy porosity method is used to model the phase change process. A fully implicit formulation is used for the time-dependent terms, and the diffusion coefficients are evaluated using central difference scheme. A line-by-line solver based on TDMA is used to iteratively solve the algebraic discretization equations.

Experimental

Four types of carbon foam cylindrical disks with different porosities and thermal conductivities are fabricated to be introduced as the solid matrix of the new composites. The carbon foam solid matrix has 51 mm diameter and 10 mm thickness and the thermal conductivities of all types are measured experimentally. Each one of the carbon foam matrices is heated under vacuum in a molten paraffin wax to achieve maximum wax absorption. All specifications of these samples are illustrated table (1). The composite is introduced into a vertical cylindrical Teflon enclosure, which has inside diameter of 51 mm and outside diameter of 102 mm. An electrical heater is introduced into a cylindrical copper disk of 51 mm diameter and 13 mm thickness. The cylindrical copper disk is installed on the top of the enclosure to provide the required heating rate. The cylindrical enclosure is well insulated from its top side while the other sides are subjected to ambient air. To attain a variable heating rate, a voltage regulator is used to supply the electrical heater with variable voltage rates. The experimental set up is shown in Fig. (1) and the thermal protection cell is shown in Fig. (2). Thermocouples of J-type are used to detect temperature at various locations inside the system. The heater surface temperature is detected by two thermocouples, one thermocouple is installed on its top surface and the other is installed on its lower surface. To detect the sample temperature history, six thermocouples are installed at different axial and radial locations in the carbon foam paraffin wax composite as shown in Fig, (3). One of these thermocouples is installed on the inner surface of the Teflon enclosure, while another one is installed on its outer surface. The thermocouples are attached to a multimeter which is connected to a PC through a standard RS-232 asynchronous serial communication port.

Table (1) Properties of the carbon foam composites

	POCO-HP	CF0514	POCO	POCO-HT
Sample Volume, m ³	2.03E-05	2.03E-05	2.03E-05	2.03E-05
Mass before saturation, gm	7.10E+00	1.15E+01	1.03E+01	1.95E+01
Mass after saturation, gm	2.01E+01	2.06E+01	2.10E+01	2.64E+01
Wax Mass, gm	1.30E+01	9.14E+00	1.07E+01	6.89E+00
Solid Carbon Volume, m ³	3.94E-06	6.37E-06	5.72E-06	1.09E-05
Void Volume, m ³	1.64E-05	1.39E-05	1.46E-05	9.45E-06
Porosity	8.06E-01	6.86E-01	7.18E-01	4.66E-01
Wax Volume, m ³	1.46E-05	1.03E-05	1.20E-05	7.74E-06
Wax Active Porosity	7.20E-01	5.06E-01	5.92E-01	3.81E-01
Thermal Conductivity, W/m .K	9.80E-01	7.00E-01	1.20E+01	1.40E+01

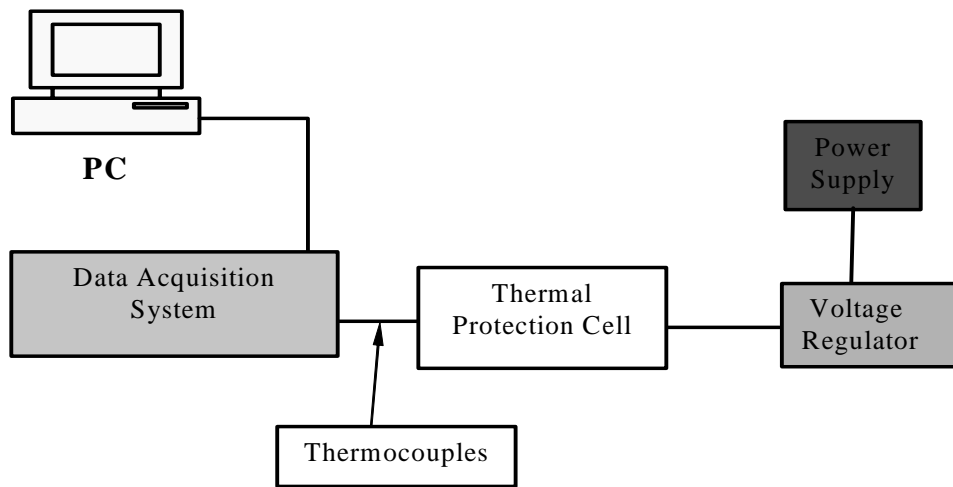


Fig. (1) Experimental setup

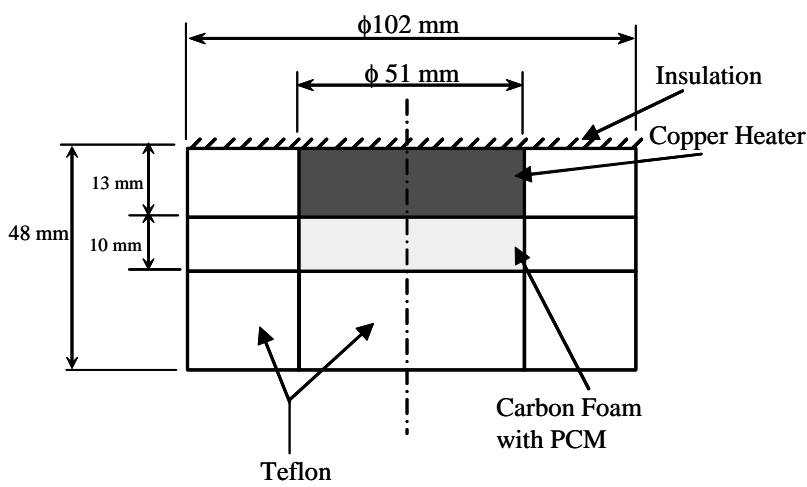


Fig. (2) Thermal protection cell

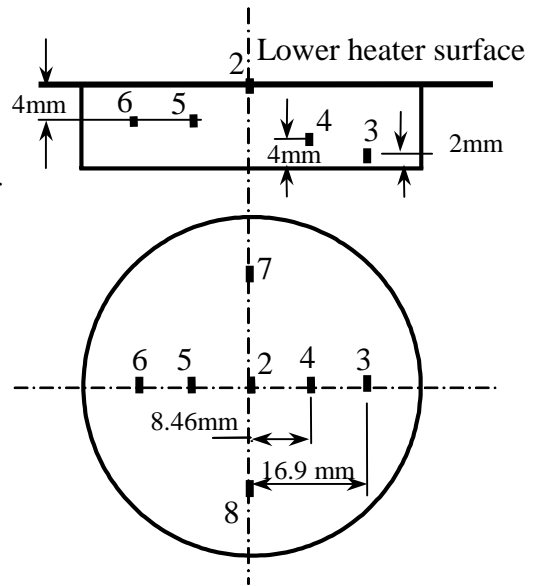


Fig. (3) Thermocouple locations

Numerical model

The numerical analysis is based on solving the heat diffusion equation in the pure solid materials such as Teflon and heating element. The volume averaging energy equation with phase change is used to model the heat transfer process inside the porous composite with phase change. Due to the small size of the carbon foam pores and experiencing the heat from the upper surface, it was found that the convection motion of liquid phase is negligible. So, the conservation of mass and momentum are omitted from the governing equations and the problem is modeled in a pure conduction mode. The contact between the different surfaces such as Teflon, carbon composite, and the heater is considered by assuming a certain value of contact resistance. Because of the symmetry, the system is formulated in two-dimensional axi-symmetric coordinates. The outer sides and bottom surface of the enclosure are assumed to be subjected to free convection, while the upper surface is insulated. The heating power is presented by introducing a heat generation source in the heater material.

Assumptions and governing equations

The mathematical formulations have been done based on the following assumptions:

- 1- The properties of each material is isotropic
- 2- The thermo-physical properties are constant with temperature
- 3- The mechanical energy for the volume change during phase change is ignored
- 4- The heat generation inside the heater is assumed to be uniform

Based on these assumptions, the energy equation for the heating element will take the following form:

$$\rho_h c_h \frac{\partial T_h}{\partial t} = \nabla \cdot (k_h \nabla T_h) + \dot{q} \quad (1)$$

Where, \dot{q} is the heat generation per unit volume inside the heating element and the subscript h refers to the heater.

The energy equations for carbon foam and PCM can be written as:

PCM Energy Equation

$$\varepsilon(\rho c)_{\text{PCM}} \frac{\partial T_{\text{PCM}}}{\partial t} = \nabla \cdot (k_{\text{eff}} \nabla T_{\text{PCM}}) + h_{\text{sf}} a_{\text{sf}} (T_s - T_{\text{PCM}}) - \rho_{\text{PCM}} L \varepsilon \frac{df}{dt} \quad (2)$$

Solid Energy Equation

$$(1 - \varepsilon)(\rho c)_s \frac{\partial T_s}{\partial t} = \nabla \cdot (k_{\text{eff}} \nabla T_s) - h_{\text{sf}} a_{\text{sf}} (T_s - T_{\text{PCM}}) \quad (3)$$

Where, ε is the carbon foam porosity. The subscripts PCM and s stand for the phase change material and the carbon solid phases, respectively. While, k_{eff} , a_{sf} , and h_{sf} are the effective thermal conductivity, interfacial area per unit volume, and the heat transfer coefficient between the solid and PCM, respectively. All of these parameters depend on the structure of the porous medium and the volume fractions of each constituent. In the

case of local thermal equilibrium, $T_{PCM}=T_s=T$, the two energy equations for solid matrix and PCM can be added together to give,

$$(\rho c)_{\text{eff}} \frac{\partial T}{\partial t} = \nabla \cdot (k_{\text{eff}} \nabla T) - \rho_{\text{PCM}} L \varepsilon \frac{df}{dt} \quad (4)$$

Where, $(\rho c)_{\text{eff}} = \varepsilon(\rho c)_{\text{PCM}} + (1-\varepsilon)(\rho c)_s$ is the effective heat capacity. L is the heat of fusion of the PCM, and f is the liquid fraction. The effective thermal conductivity of the foam is measured experimentally for all the samples and the experimental values have been used in the numerical model.

Numerical technique

The heat equation is discretized using a finite volume approach. A typical control volume is shown in Fig. (4). A fully implicit formulation was used for the time-dependent terms, and the diffusion coefficients are evaluated using central difference scheme. A line-by-line solver based on TDMA is used to iteratively solve the algebraic discretization equations, [10].

The general difference equation takes the form:

$$(a_p - S_p)\phi_p = \sum a_n \phi_n + a_p^o \phi_p^{\text{old}} + Su \quad (5)$$

The variables S_p and Su are used to linearize any source term S such that:

$$\int S dV = S_p \phi_p + Su$$

The subscript n stands for the neighboring points E, W, S, and N.

Using the central difference scheme, the coefficients will take the following forms:

$$a_E = \frac{k_e r_e \Delta z}{\Delta r_e} \quad a_W = \frac{k_w r_w \Delta z}{\Delta r_w} \quad a_N = \frac{k_n r_n \Delta r}{\Delta z_n} \quad a_S = \frac{k_s r_s \Delta r}{\Delta z_s}$$

$$a_p^o = \frac{\rho c \Delta V}{\Delta t} \quad a_p = a_w + a_E + a_S + a_N + a_p^o \quad (6)$$

At any contact between two different materials, a thermal resistance is introduced for calculating the heat diffusion coefficient which appears in equation (6). The contact resistance between the heating surface, matrix composite, and the enclosure walls is taking into consideration by applying one dimensional heat conduction approximation. If the contact surface coincides with the south surface of the control volume, the value of heat diffusion coefficient k_s will be calculated as the inverse of the total thermal resistance between points S and P as shown in Fig.(5).

$$k_s = \frac{1}{\frac{1}{2k_{m1}} + \frac{R_{\text{contact}}}{\Delta z} + \frac{1}{2k_{m2}}}$$

Where, k_{m1} and k_{m2} are the thermal conductivities of the two contacting materials. The thermal resistance is assumed to be of the order of 0.001 ($\text{m}^2\text{K/W}$).

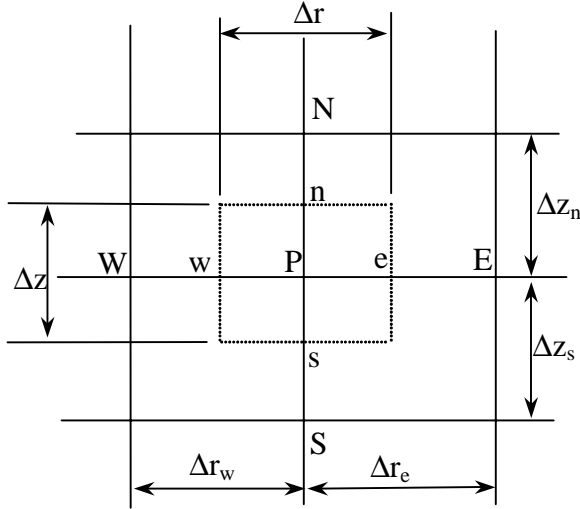


Fig. (4) Numerical control volume

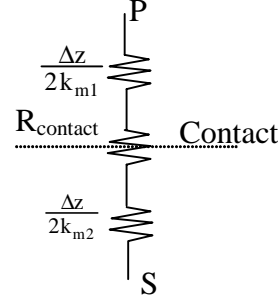


Fig. (5) Contact resistance

The liquid fraction for each computational cell is updated using a reliable iterative method. At any iteration, if the phase-change happens, the temperature will be set at the melting temperature and the liquid fraction will be updated.

$$a_p T_m = \sum a_n T_n + a_p^o T_p^{old} - \frac{\rho L \epsilon \Delta V}{\Delta t} (f^{n+1} - f^{old})$$

Subtracting this equation from the original discretized energy equation, this will give the following iterative formula:

$$f^{n+1} = f^n + \frac{a_p}{L \epsilon} \left(\frac{\Delta t}{\rho \Delta V} \right) (T_p - T_m)$$

For stability purpose, the liquid fraction is calculated from:

$$f^{n+1} = \alpha_f f^{n+1} + (1 - \alpha_f) f^n$$

Where α_f is the under-relaxation factor for updating the liquid-fraction. The value of α_f is assumed to be between 0.1 and 0.2.

Convergence Criteria

The convergence criteria for the numerical solution of the heat equation are based on the energy imbalance within the system. The unsteady energy imbalance was calculated as the difference between the heat generated by the heating element and the sum of the heat absorbed by the material in the system as sensible or latent heat and the heat loss to the atmosphere each time step.

$$Q_{error} = Q_{heater} - Q_{latent} - Q_{sensible} - Q_{loss}$$

Convergence is assumed to be achieved for energy imbalance equal to 0.001.

Results and discussion

The experimental and numerical studies have been carried out for four types of carbon foam as shown in table (1) and under variable heat inputs to perform the required parametric study. Figure (6) shows the experimental and numerical results for the temperature time history at different locations in the matrix composite CF0415, which has low thermal conductivity and medium porosity, under different heat inputs. The

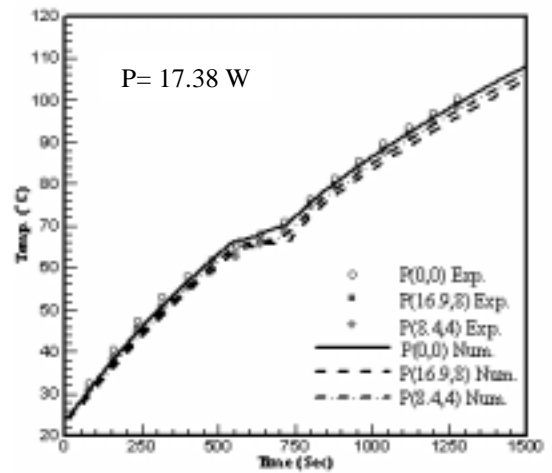
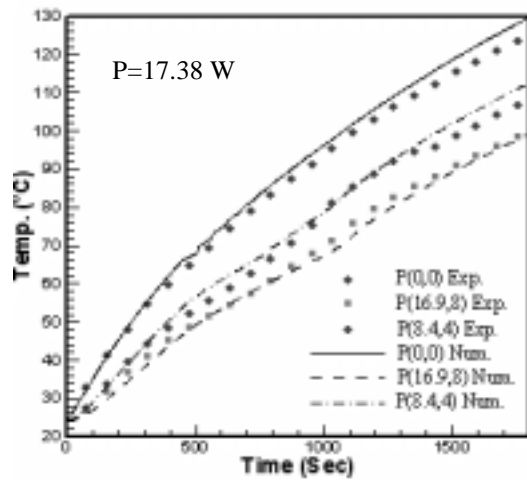
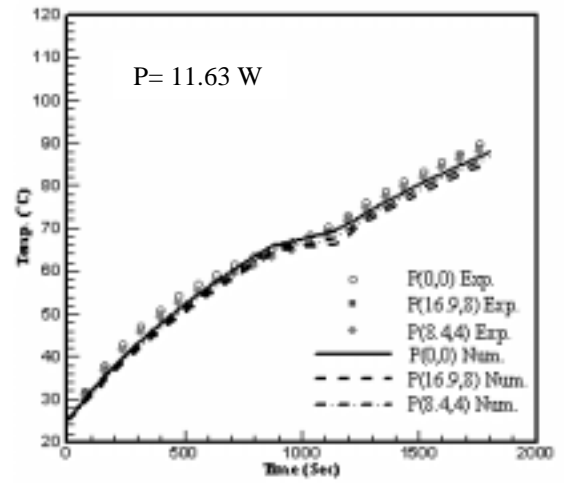
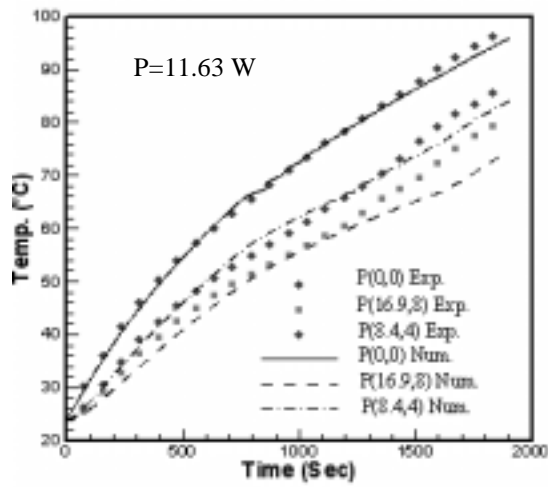
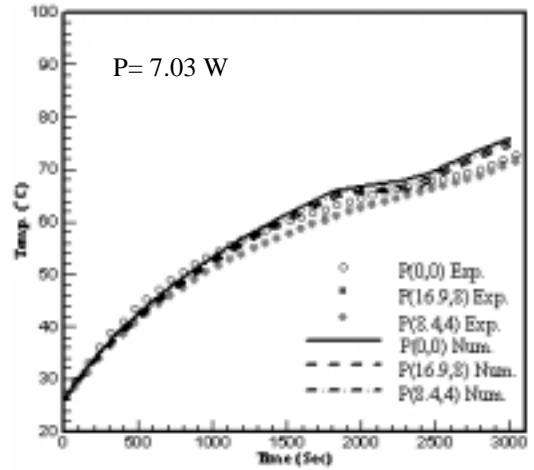
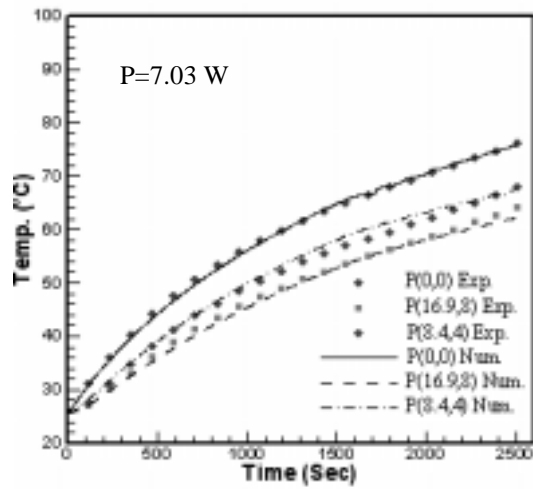


Fig. (6) Temperature time history for the matrix composite, 0514 at different power inputs

Fig. (7) Temperature time history for the matrix composite, POCO at different power inputs

experiments are performed under three input power levels, 7.04, 11.63, and 17.38 Watt. The numerical and experimental results show a good agreement. It is shown from the figure that the maximum temperature is attained on the heating element surface, $P(0,0)$, while the temperature decreases when we go down through the axial direction. The rate of increase of temperature decreases clearly inside the porous composite at temperature between 60 to 70 °C which is the melting temperature of the PCM. This temperature rate decrease is evident at high power input cases. In the case of low heat input the temperature increases slowly which causes a slow rate of the melting process of the PCM.

Figure (7) shows the experimental and numerical results of the temperature time history for carbon matrix composite POCO which has higher thermal conductivity. In the case of high thermal conductivity porous foams, the temperature difference between the axial locations is very small compared to those of the low thermal conductivity. Figure (8) shows the numerical results of the temperature time history of the lower heating surface for all the samples at different heat inputs. The figure shows that the lowest temperature of the heating surface is achieved according to this sequential, POCO, POCO-HT, POCO-HP and finally CF0415. Out of this it can be concluded that controlling the surface temperature depends mainly on two parameters. The first one is the thermal conductivity of the carbon foam and the second is the carbon foam porosity. The higher the thermal conductivity and the higher the porosity the lower of the heater surface temperature.

Figure (9) represents the heat absorption rate by the matrix composite over the input heat rate for all cases. From the figure, one can see that for all the cases, the heat absorption rate by the matrix composite is increased rapidly in the early stage of heating process due to the temperature difference between the heating surface and the matrix composite. After this period the heat absorption rate by the matrix composite decreases until the PCM begins to melt. During the melting process of the PCM inside the matrix pores, the heat absorption rate by the matrix composite increases sharply to the maximum value due to the latent heat of the PCM then decreases again but in this time to a level higher than that of the early stage. By performing a comparative study between all the cases we can conclude that, the amount of the PCM inside the matrix pores, which is depending mainly upon the porosity of the solid matrix, controls and expands the heat absorption duration time during the heating process by a direct proportional relation. On the other hand, the thermal conductivity of the matrix composite plays an important role in the heat absorption rate. The highest the value of the thermal conductivity of the matrix composite, the highest the value of the heat absorption rate but through a small time interval because this highest value of the thermal conductivity acts to conduct the heat rapidly and so acts to absorb heat rapidly. So, we will have a compromise situation according to the applied application. We can also conclude from the figure that the heat absorption rate by the matrix composites increases with the increase of the applied heat input.

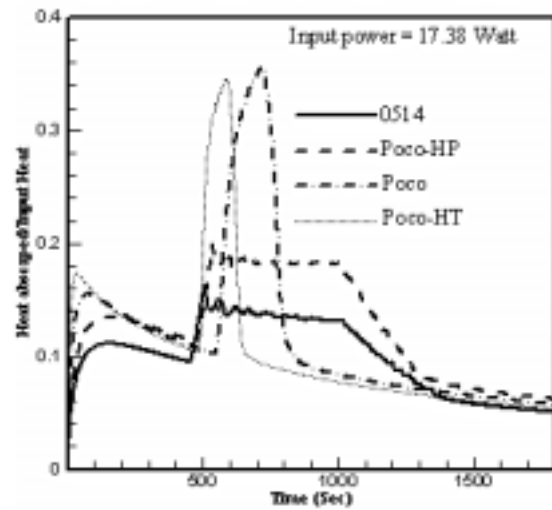
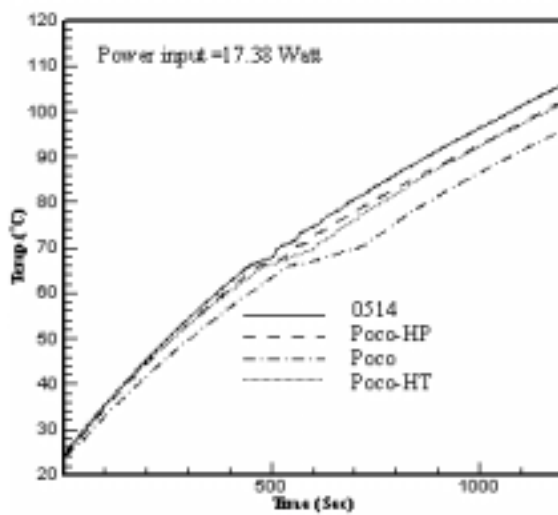
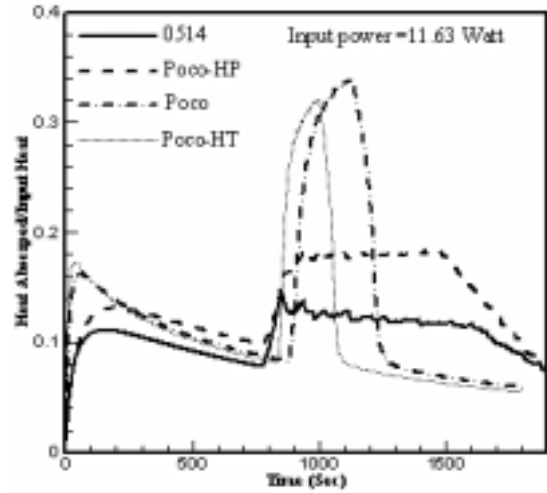
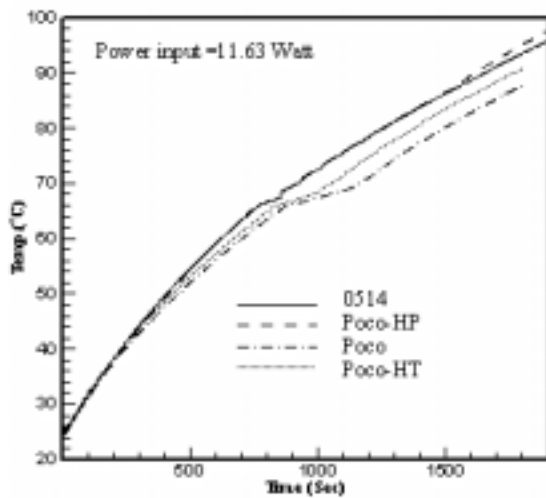
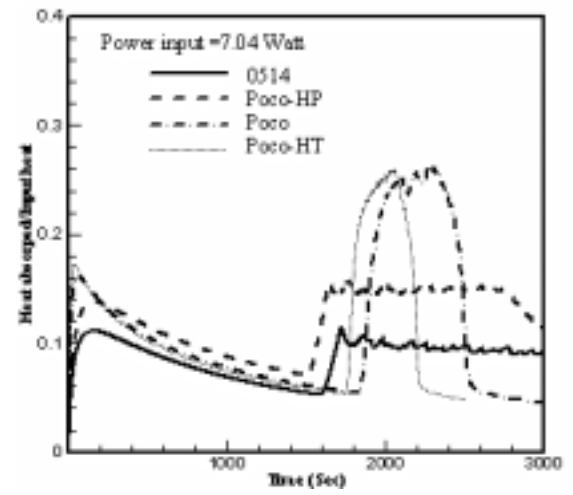
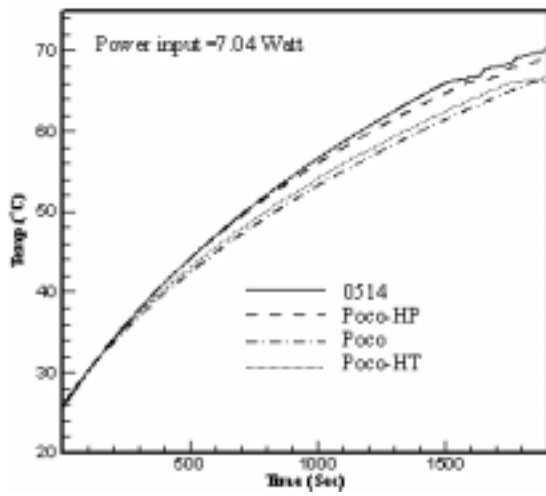


Fig. (8) Temperature time history of the heating surface at different power inputs

Fig. (9) Heat absorption rate for all samples at different power inputs

Conclusions

The effect of the porosity and thermal properties of a porous medium filled with PCM are studied numerically and experimentally. Carbon foam matrices with different porosities and thermal properties are introduced as the porous medium while paraffin wax is introduced as the PCM occupies the matrix pores. The matrix composite is introduced into a cylindrical enclosure while it experiences its heat from a heat source setting on the top of the enclosure. The experimental and numerical results showed good agreement which indicates that the assumptions and numerical model proceedings are accepted. The PCM active porosity and thermal conductivity of the matrix composite play important roles in their thermal performance. The highest the active porosity of the PCM inside the matrix pores, the more stability of the thermal performance of the matrix composite. On the other hand, the thermal conductivity of the composite matrix acts sharply to increase or decrease its heat absorption rate. According to these last statements we will have a compromise situation between the thermal stability of the matrix composite and its ability to absorb or conduct heat.

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