

Numerical investigations of using carbon foam/PCM/Nano carbon tubes composites in thermal management of electronic equipment



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ABSTRACT

A numerical investigation of predicting thermal characteristics of electronic equipment using carbon foam matrix saturated with phase change material (PCM) and Nano carbon tubes as thermal management modules is presented. To study the effect of insertion of RT65 and Nano carbon tubes in carbon foam matrices of different porosities, three different modules; namely Pure CF-20, CF20 + RT65, and CF-20 + RT65/Nano carbon modules are numerically tested at different values of carbon foam porosities. Mathematical model is obtained using volume averaging technique based on single-domain energy equation and a control volume based numerical scheme. Interfacial effects influencing heat transfer process at enclosure wall, module surface and different interfacial surfaces within the composite have been addressed. Governing equations have been solved using a CFD code (Thétis, <http://thetis.enscbp.fr>). Mathematical model is validated by comparing its prediction with previous experimental measurements for pure CF-20 foam and CF-20 + RT65 composite modules. The model is used to predict thermal characteristics of CF-20 + RT65/Nano carbon tubes composite as a thermal management modules. Results reveal that insertion of RT65/MWCNTs in CF-20 leads to a 11.5% reduction in the module surface temperature for carbon foam porosities less than 75%. The reduction decrease to 7.8% for a porosity of 88%. Numerical results of transient and steady state temperature histories at different depths within the module are compared with previous experimental data and fair agreement is obtained.

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1. Introduction

Porous media has been widely used for thermal management (TM) of many engineering applications especially electronic equipment [1,2]. Main advantage of a porous system in such applications is its high surface area-to-volume ratio which leads to enhanced heat transport and miniaturization of thermal systems. Foam materials is a highly permeable porous medium characterized by the presence of two or more phases. One of these phases is solid phase and the other can be fluid or just void spaces. In open cell metal or carbon foams, void spaces are connected to each other leading to high permeability. Effective thermal conductivity, interfacial surface area, and permeability are the properties that control performance of thermal management modules and heat sink. Open cell metal foams have favorites values of these properties which make them highly recommended as a heat sink for thermal management of electronic devices.

On the other hand phase change materials (PCMs) are widely recommended for thermal management of electronic devices subjected to high heat densities and cyclic temperature variations. Absorbing and storing thermal energy using PCMs are typically used to reduce temperature variations of components that are subjected to periodically varying boundary conditions. Thermal diffusivity of phase change materials is an important property controlling heat transfer characteristics of PCMs. Since it determines the ability of PCM material to conduct thermal energy relative to its ability to store energy.

Low thermal conductivity of PCM has been a major concern in view of the widely adopted and stringent requirement to store/release (charge/discharge) thermal energy over a desired time period. Consequently, enhancement of thermal conductivity of PCMs has been a major focus of thermal energy storage researches. Combining PCMs of low thermal conductivity with highly conductive materials is a logical solution to come up with new material processing with enhanced effective thermal conductivity. Placement of metal fillers, foams, wools into the PCM has been investigated and practiced in the last two decades.

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Nomenclature

$corr$	correction factor, dimensionless
c_p	specific heat (J/kg K)
g_l	liquid fraction of the fluid phase, dimensionless
h_L	liquid phase enthalpy (J/kg)
k_{eff}	effective thermal conductivity (W/m K)
L	latent heat (J/kg)
T	temperature (K)
T_{onset}	PCM melting onset temperature (K)
T_{endset}	PCM melting endset temperature (K)
T_p	phase change temperature (K)
S_T	source term, dimensionless
V	volume (m ³)
V_f	volume of phase change material (m ³)
V_l	liquid volume of solid–liquid phase (m ³)
ε	carbon foam porosity
δ	liquid fraction in the REV element, dimensionless
ρ_s	phase change material solid density (kg/m ³)
ρ_l	phase change material liquid density (kg/m ³)

Subscripts

f	fluid phase (phase change material)
s	carbon foam solid phase
p_s	carbon foam solid
L	liquid phase
s	solid phase

Abbreviations

PCMs	phase change materials
PW	paraffin wax
MWCNTs	Multi Walled Carbon Nano-tubes
CNTs	carbon nanotubes
CF-20	carbon foam type CF-20
RT65	commercial grade of paraffin wax, supplied by RUBITHERM, Germany
CF	carbon foam
CFD	computational fluid dynamics
REV	representative elementary volume

Recently, the approach of utilizing the advantages of carbon foam and PCMs and eliminating the short comings of both of them in thermal management of electronic devices, by constructing a composite structure was proposed. Carbon foam provide thermal conductivity enhancer for the PCMs. A number of recent studies on the enhancement of the thermal conductivity of PCMs have focused on use of a porous matrix. Hoogendoorn and Bart [3] reported that the low thermal conductivity of the PCMs can be greatly enhanced by embedding PCM within a metal matrix structure. Ettouney et al. [4] used metal screens/spheres placed inside the PCMs. Mauran et al. [5] used a solid matrix made of graphite as a support for low thermal conductivity reactive salts. Alawadhi and Amon [6] carried out an experimental and numerical investigation of a TM unit for portable electronic devices. The experimental model used aluminum foam impregnated with Eicosane PCM contained in an aluminum enclosure. A numerical study was also carried out using finite element method to conduct a parametric analysis under realistic boundary conditions. Lafdi et al. [7] carried out an experimental investigation to study heat transfer within a composite of phase change material (PCM) infiltrated in high thermal conductivity foam. Aluminum foams with different pore size and porosity were used as the porous material, and low melting temperature paraffin wax was used as the PCM. Khateeb et al. [8,9] investigated the utilization of aluminum foams filled with paraffin wax (PCM) as a passive thermal management system for a lithium-ion battery. Other researchers used porous graphite to improve wax thermal properties [10–14]. However; the graphite seems to lead to certain anisotropy in terms of the thermal conductivity [13]. Hong and Herling [15] analyzed the effects of geometric parameters of foam on the thermal performance of PCM/aluminum foam heat sinks. They concluded that the aluminum foams with larger surface area density utilized more latent heat within a given period of time which helped in improving the thermal performance of the heat sink. Weaver and Viskanta [16] performed numerical and experimental investigations for phase change of water in saturated porous media contained in various enclosures. Solid–liquid interface and fluid motion were observed directly. The effects of natural convection and porous media (spherical glass balls) on the solidification and fluid motion were reported. Kermann and Viskanta [17] carried out numerical and experimental studies for solid/liquid phase change in porous media with natural convection in the molten region. Natural convection in

the melt as well as heat conduction in the solid is found to considerably influence the interface shape and movement during both melting and solidification process.

The process of studying thermal behavior of a system consisting of PCM and foam is very complicated due to the difference in thermal properties of the foam and the PCM, which has been defined as thermal non-equilibrium by some authors [2]. The phenomenon of thermal non-equilibrium can be ignored when the thermal properties of the two phases are close to one another. Some of the works in literature [13] considered local thermal equilibrium between the solid matrix and the PCM since the thermal conductivity of porous matrix was low and close to the value of PCM. Mesalhy et al. [18] carried out numerical and experimental studies to investigate the thermal characteristics of a cylindrical thermal protection system made of carbon foam matrix saturated with PCM. Their results illustrated that the stability of the thermal performance of composite matrix was dependent on the porosity of the foam and was better for higher porosity foams. Quintard and Whitaker [19] carried out an extensive analysis to determine the conditions for local thermal equilibrium. They concluded that the deviation from local thermal equilibrium would be significant if there is a large difference between the physical properties of the fluid and solid phases. Mesalhy et al. [20] performed a numerical study to analyze the phase change process in a PCM/foam cylindrical composite. They used the volume averaged technique to solve the conservation equations of mass, momentum, and energy with phase change inside the porous matrix. The critical problem of local thermal non-equilibrium was addressed by using separate energy equations for the two phases. More recently, Lafdi et al. [21] proposed a numerical study to investigate and predict the thermal performance of graphite foams infiltrated with phase change materials, PCMs, for space and terrestrial energy storage systems. The numerical model is based on a volume averaging technique while a finite volume method has been used to discretize the heat diffusion equation. They concluded that the high thermal conductivity of graphite foams, the PCM-foam system thermal performance has been improved significantly. Zhong et al. [22] used a Mesophase pitch based graphite foams (GFs) with different thermal properties and pore-size to increase the thermal diffusivity of phase change material (PCM), paraffin wax, for latent heat thermal energy storage application. Their results indicated that thermal diffusivity of the Paraffin-GF can be enhanced 190, 270, 500, and 570 times as

compared with that of pure paraffin wax. Latent heat of Paraffin-GF systems increased with the increasing of the mass ratio of the paraffin wax in the composite. Yang and Garimella [23] investigated the melting of phase change materials (PCMs) embedded in metal foams. The two-temperature model developed accounts for volume change in the PCM upon melting. Effects of volume shrinkage/expansion are considered for different interstitial heat transfer rates between the foam and PCM. Zhou and Zhao [24] presented an experimental study on heat transfer characteristics of PCMs embedded in open cell metal foams and expanded graphite, respectively. In that study the paraffin wax RT27 and calcium chloride hexahydrate are employed as the heat storage media and the transient heat transfer behavior is measured. The results indicate that the addition of porous materials, either open-cell metal foams or expanded graphite, can enhance the heat transfer rate of PCMs. Zhao et al. [25] investigated experimentally the solid/liquid phase change (melting and solidification) processes of PCM infiltrated in metal foam. Paraffin wax RT58 is used as phase change material (PCM), in which metal foams are embedded to enhance the heat transfer. Phase change material (PCM) composites based on low-density polyethylene (LDPE) with paraffin waxes were investigated in the study of Trigui et al. [26]. The composites were prepared using a melt mixing method with a Brabender-Plastograph. The LDPE as the supporting matrix kept the molten waxes in compact shape during its phase transition from solid to liquid. The operation and operating parameters of a small-scale Thermal Energy Storage (TES) device that collects and stores heat in a phase change material (PCM) was explored by Thapa et al. [27]. They studied the fabrication and analysis of small-scale thermal energy storage with conductivity enhancement. Lachheb et al. [28] studied the effect of combining two types of graphite (Synthetic graphite Timrex SFG75 and graphite waste obtained from damaged Tubular graphite Heat Exchangers) with paraffin in an attempt to improve thermal conductivity of paraffin phase change material (PCM). The results showed that the thermal conductivity and thermal diffusivity are

greatly influenced by the graphite addition. Recently, Farid et al. [29] presented a review of previous work on latent heat storage and provided an insight to recent efforts to develop new classes of phase change materials (PCMs) for use in energy storage. Three aspects have been the focused of this review: PCM materials, encapsulation and applications. More recently, Raam Dheep and Sreekumar [30] carried out a review to investigate the influence of nanomaterials on properties of latent heat solar thermal energy storage materials.

The above literature showed that most of the TM methods used PCMs or PCMs with conductive additives as heat transfer enhancers. A lot of experimental studies were conducted however the numerical investigation were limited. More recently, the idea of inserting Nanocarbon tubes, as thermal characteristics enhancer, in the PCMs was experimentally introduced and tested [31,32]. The present work is focused on numerical investigation, using computational fluid dynamic software (Thétis), of the effect of insertion of paraffin wax RT65 as phase change material and Multi Wall Carbon Nano Tubes (MWCNTs) as thermal conductivity enhancer in carbon foam (CF-20) micro structure modules on the thermal management of electronic devices. CF-20 has been used as a support structure for the composite due to its high thermal conductivity which leads to an efficient TM system. To study the effect of porosity, different CF-20 modules of different porosities have been used as a support structures.

2. Physical and mathematical models

2.1. Physical model

The physical model used for the studied encapsulated composite TM modules is shown in Fig. 1. Three types of composites modules, pure CF-20 foam, CF-20 + RT65 composite and CF-20 + RT65/MWCNTs composites are studied and numerically tested. The base structures of the three modules is carbon foam

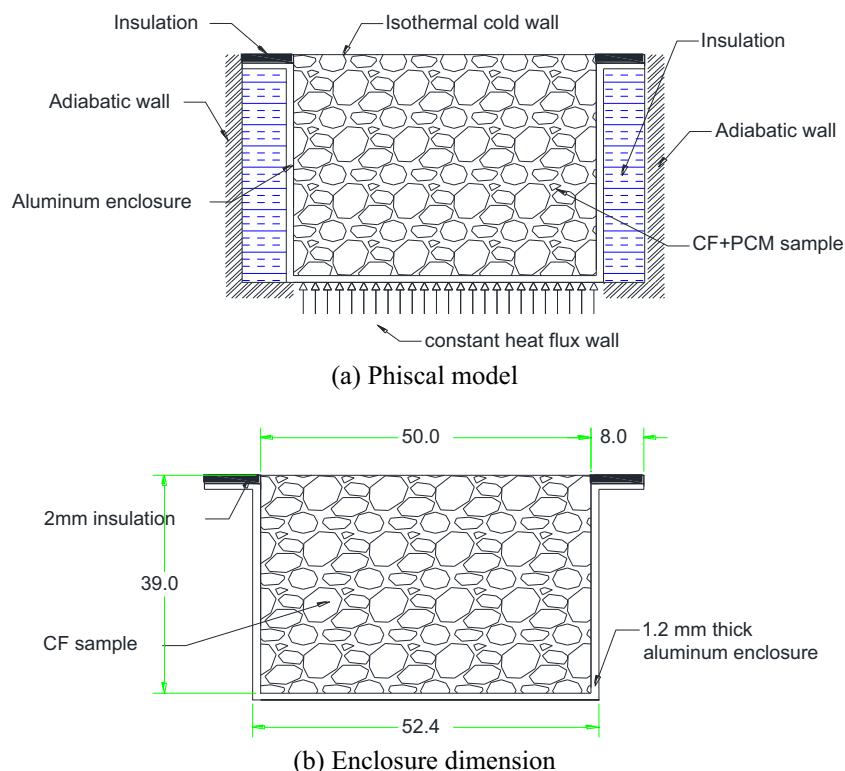


Fig. 1. Schematic diagram of physical model and enclosure dimension.

Table 1

Thermo-physical property of CF-20 carbon foam.

Carbon foam	Apparent density (kg/m ³)	Total open porosity (%)	Average pore size (μm)	Wall thickness (μm)	Thermal conductivity (W/m K)	Specific heat (J/kg K)
CF-20	250	88.00	500	17.10	3.10	750

Table 2

Thermo-physical properties of paraffin wax (RT65) [18].

Paraffin wax	Density (kg/m ³)	Melting temp. (°C)	Latent heat (kJ/kg)	Thermal conductivity (W/m K)	Thermal diffusivity (m ² /s)
RT65	880	65	152	0.20	1.08E–07

Table 3

Thermo-physical properties of aluminum container and insulation used for computations.

Property	Value
Density (aluminum)	2719 kg/m ³
Thermal conductivity (aluminum)	182 W/m K
Specific heat (aluminum)	871 J/kg K
Density (side cork insulation)	80 kg/m ³
Thermal conductivity (side cork insulation)	0.037 W/m K
Specific heat (side cork insulation)	1900 J/kg K
Density (top polyurethane insulation)	35 kg/m ³
Thermal conductivity (top polyurethane insulation)	0.038 W/m K
Specific heat (top polyurethane insulation)	1400 J/kg K

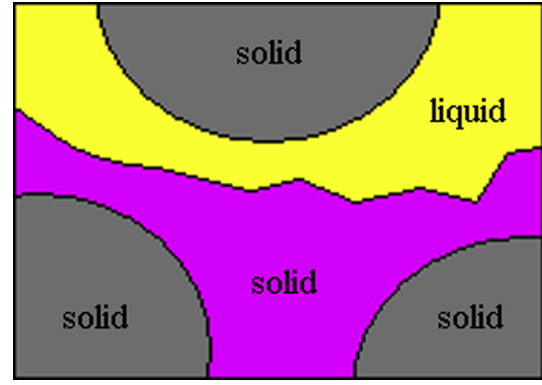
CF-20. The first module, CF-20, is pure carbon foam module. The second module (CF-20 + RT65) is carbon foam infiltrated with paraffin wax as PCM material. The third module (CF-20 + RT65/MWCNTs) is carbon foam infiltrated with a composite of paraffin wax and Nanocarbon tubes. The Nano carbon tubes is penetrated in the paraffin wax to improve its thermal performance, mainly thermal conductivity and latent heat [32]. The thermo-physical properties of the paraffin wax (RT65) and CF-20 are given in Tables 1 and 2.

TM modules are enclosed/encapsulated in a thin aluminum casing with a thickness of 1.5 mm. The module is considered to be heated from bottom side with a constant heat flux condition. The top wall of the module is maintained at a constant temperature equal to the initial temperature of the system (25 °C). The right and left sides of the module are considered adiabatic. Aluminum container and insulation properties are given in Table 3.

For the aim of numerical validations, the physical model considered in the study was selected to be similar to the TM modules that was experimentally tested by Alshaer [32].

2.2. Mathematical model

The volume averaged energy equation with phase change is used to model the heat transfer process inside the porous composite with and without PCM. Considering a representative elementary volume (REV) undergoing phase change process in a porous media as shown in Fig. 2. The REV of volume “V” contains the carbon foam solid phase “s”. The porous pores of carbon foam of porosity “ε” are filled with phase change material with volume “V_l”. In the present analysis, the properties of each phase are assumed isotropic and constant. The solid–liquid phase change

**Fig. 2.** REV for phase change in a porous media.

takes place in the fluid phase. The fraction liquid in the fluid phase is defined as:

$$g_l = \frac{V_l}{V_f} \quad (1)$$

where V_l is the liquid volume in the fluid phase.

The liquid fraction “ δ ” in the REV element is defined as:

$$\delta = \varepsilon g_l \quad (2)$$

where $\varepsilon = \frac{V_f}{V}$ is the carbon foam porosity.

It should be mentioned that there are two solid phases inside the REV. The PCM solid referred by the subscript “s” and the carbon foam solid referred by the subscript “ps”. Due to the small size of the carbon foam pores, which is ranging between 200 and 800 μm, it is assumed that the convection motion of the molten liquid phase is negligible. This assumption is supported by [20,25] where the convection motion is neglected due to the small size of the pores. Also the assumption of neglecting the convection motion liquid phase is supported by the findings of [33] who examined the role of natural convection within the pores by discretizing and solving the continuity and momentum equations numerically over the fluid domain. They found that the role of natural convection within the pores turned out to be negligible due to the small values of the pore diameter and temperature difference (the Grashof and Rayleigh numbers based on the pore diameter are of the order of 1 and 10, respectively).

Assuming thermodynamic equilibrium between the solid (s and ps) and liquid (l) phases, the volume averaged energy equation for the porous matrix (ps)/solid (s)/liquid (l) can be written as

$$\frac{\partial}{\partial t} [\varepsilon (g_l \rho_l h_l + (1 - g_l) \rho_s h_s) + (1 - \varepsilon) \rho_{ps} h_{ps}] = \nabla \cdot (k_{eff} \nabla T) + S_T \quad (3)$$

where k_{eff} is the effective thermal conductivity and S_T accounts for other source terms. For a volume element undergoing phase change (i.e. for $0 < g_l < 1$), a change in the main enthalpy of the fluid is due to a change in the sensible heat of the liquid/solid mixture plus contribution of the latent heat. To a good approximation, this can be expressed as:

$$d(g_l \rho_l h_l + (1 - g_l) \rho_s h_s) = (g_l (\rho c_p)_l + (1 - g_l) (\rho c_p)_s) dT + \rho_l L dg_l \quad (4)$$

where L is the latent heat of phase change. The liquid phase enthalpy is given by:

$$h_l = (c_p)_l T + L \quad (5)$$

Substituting Eqs. (5) into (3) results in:

$$\frac{\partial (\rho c_p T)}{\partial t} = \nabla \cdot (k_{eff} \nabla T) - \varepsilon \rho L \frac{\partial g_l}{\partial t} = S_T \quad (6)$$

where:

$$k_{eff} = (1 - \varepsilon)k_{ps} + \varepsilon(g_l k_l + (1 - g_l)k_s) \quad (7)$$

and:

$$\overline{\rho c_p} = (1 - \varepsilon)(\rho c_p)_{ps} + \varepsilon[g_l(\rho c_p)_l + (1 - g_l)(\rho c_p)_s] \quad (8)$$

Eq. (6) is applicable to the whole domain by proper assignment of thermo-physical properties, porosity, solid and fluid phases. The governing equation (Eq. (6)) contains an extra unknown “ g_l ” which is function of the temperature. Iterations for g_l are obtained as follows:

$$g_l^{i+1} = g_l^i + corr \quad (9)$$

where i refer to the iteration number and $corr$ is the correction term given by:

$$corr = \frac{c_p(T^i - T_p)}{L} \quad (10)$$

where T_p is the phase change temperature. At convergence $T_i = T_p$ and $corr = 0$.

For phase change materials undergoing phase change at a given constant phase change temperature, T_p is a constant value independent of liquid fraction g_l .

In the present PCM undergoes solid/liquid phase change over a temperature range between T_{onset} and T_{endset} , a linear variation of T_p is assumed as follows:

$$T_p = T_{onset} + g_l(T_{endset} - T_{onset}) \quad (11)$$

The above system of equations subjected to the following boundary and initial conditions as shown in Fig. 1

- Constant heat flux of 12,000 W/m² applied at bottom of the system.
- Top wall temperature is constant and equal to the initial temperature of the system.
- Initial temperature of the system = 25 °C.

The above governing equation has been solved using a CFD code (Thétis, <http://thetis.enscbp.fr>). Thétis employs a finite volume discretization of the governing equations. The discretized equations are solved using iterations at a given time step and considered converged when the residual is less than 10^{-15} . Internal iterations for liquid fraction are considered converged when $corr \leq 10^{-6}$. A time step of 1 s has been implemented in all simulations.

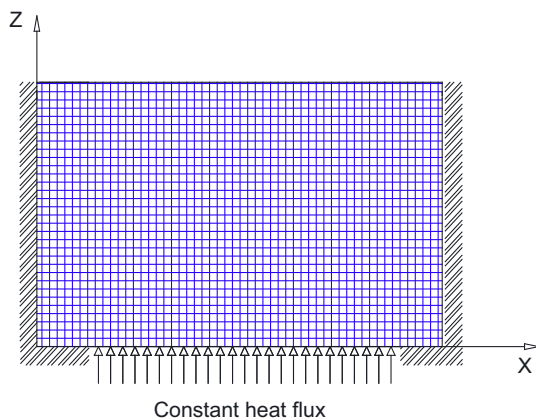


Fig. 3. Grid shape.

3. Grid independent study and code validation

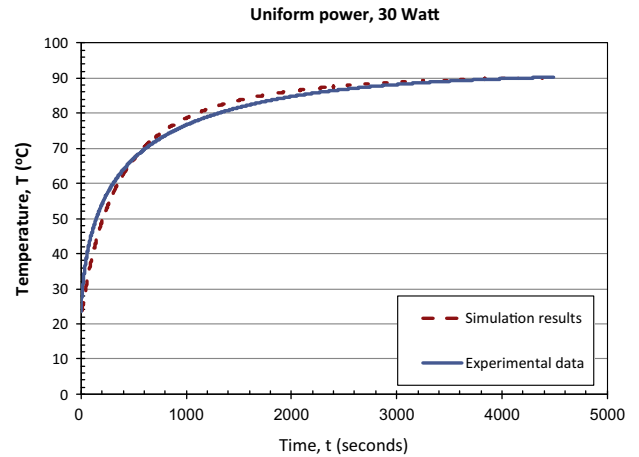
3.1. Grid independent study

The grid generation for whole domain described in Fig. 1 for pure CF-20, CF-20 + RT65 and CF-20 + RT65/MWCNTs modules are shown in Fig. 3. A grid sensitivity analysis has been performed to reach the proper grid size for grid independent results. Table 4 shows the steady state temperature of the heater surface at different values of grid sizes and 1 s time step for pure CF-20,

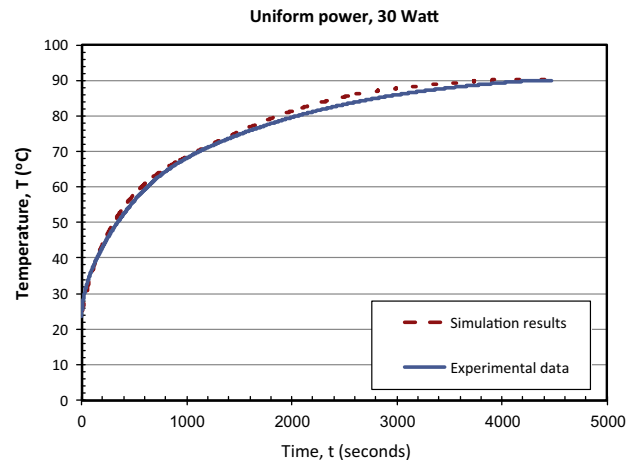
Table 4

Steady state temperature values at different grid sizes for pure CF-20, CF-20 + RT65 and CF-20 + RT65/MWCNTs modules.

Grid size	Pure CF-20 T (°C)	CF-20 + RT65 T (°C)	CF-20 + RT65/ MWCNTs T (°C)
70 × 35	86.48	89.58	82.52
90 × 60	87.96	90.35	83.31
150 × 100	89.71	91.10	83.85
180 × 120	90.10	91.31	84.23
220 × 150	90.44	91.51	84.37
260 × 180	90.67	91.66	84.52
310 × 210	90.76	91.78	84.64
370 × 250	90.84	91.80	84.66
444 × 300	90.86	91.82	84.67



(a) pure CF-20 module



(b) CF-20+RT65 module

Fig. 4. Code validation by comparing code predictions for modules top surface temperature with previous experimental data [32].

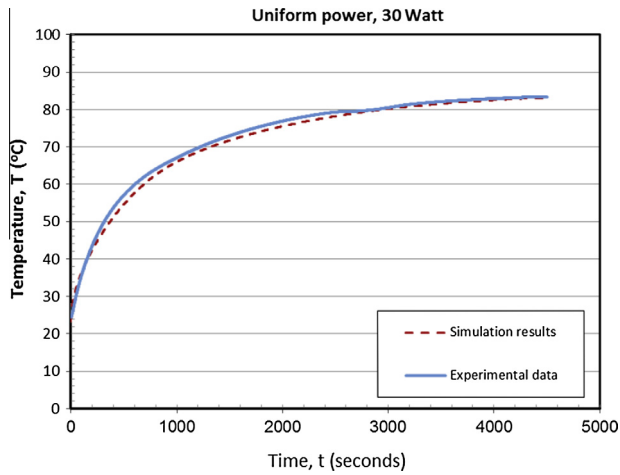


Fig. 5. Code prediction for CF-20 + RT65/MWCNTs module compared with Alshaer [32] experimental data.

CF-20 + RT65 and CF-20 + RT65/MWCNTs modules. Different time steps values of 0.01 s, 0.1 s, and 1 s have been implemented in the study. It has been observed that there is no discrepancy between the numerical values of Table 4 at the different time steps. This is attributed to the implicit nature of the energy equation and the absence of advection terms. As shown in the table the temperature history becomes constant within an error of 0.0002 °C (0.02%) for grid size of 370×250 and more. Therefore a time step of 1 s and a grid size of 370×250 have been implemented in all simulations in order to reduce the computer run time. The validation of the selected grid size and time step is also done by comparing the time history of heater surface temperature with previous

experimental data [32] of the same physical model. The following section shows this validation.

3.2. Code validation

Validations of the present mathematical model have been carried out by comparing code prediction of modules surface temperature with previous experimental results. Fig. 4 shows the comparison of code predictions with experimental data of Alshaer [32] obtained for pure CF-20 module and CF-20 + RT65 modules of 0.88 porosity and having same physical dimensions and boundary conditions of the one considered in the present numerical study. As shown in the figure, the model perfectly predicts the experimental results.

3.3. Prediction of CF-20 + RT65/MWCNTs effective thermal conductivity

No data (theoretical estimation or measurements) are available in the literature regarding predicting the effective thermal conductivity of CF-20 + RT65/MWCNTs. Based on code validations proved in Fig. 4 (which proves that the code can perfectly predict the temperature response of the module surface temperature), an iteration technique was used to find the values of k_s , k_L and k_{eff} (see Eq. (7)) that accurately predict the experimental data of Alshaer [32] for CF-20 + RT65/MWCNTs modules. It was found that a value of $k_s = k_L = 0.6$ W/m K is required to predict the experimental data of Alshaer [32]. These values give an enhancement of k_{eff} of CF-20 + RT65/MWCNTs modules by about 16.1% as compared to pure CF-20 modules. This increase can be attributed to the formation of conductive structure of RT65/MWCNTs on the micro-scale inside the carbon foam pores. The code prediction of CF-20 + RT65/MWCNTs modules utilizing this enhancement in k_{eff}

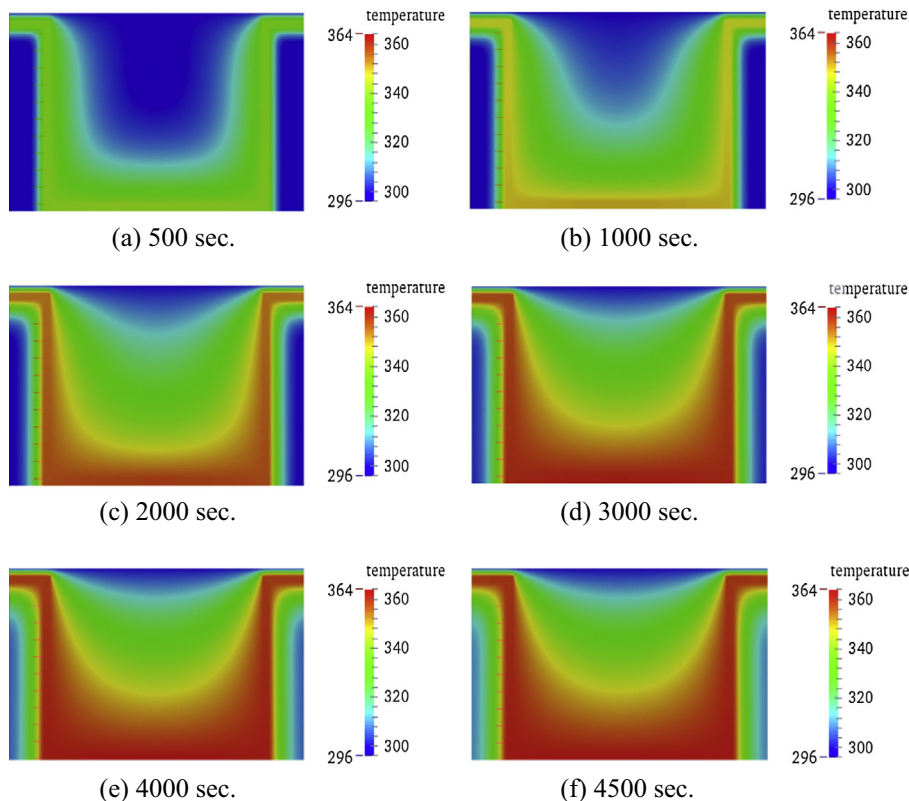


Fig. 6. Temperature distribution at different times for CF-20 module.

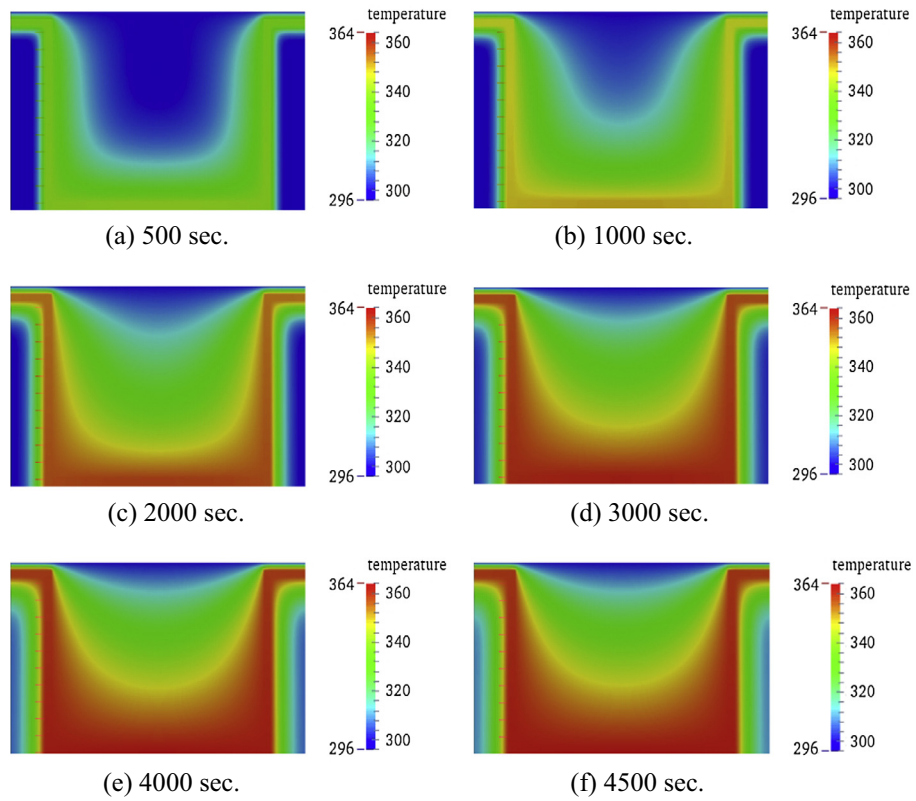


Fig. 7. Temperature distribution at different times for CF-20 + RT65 module.

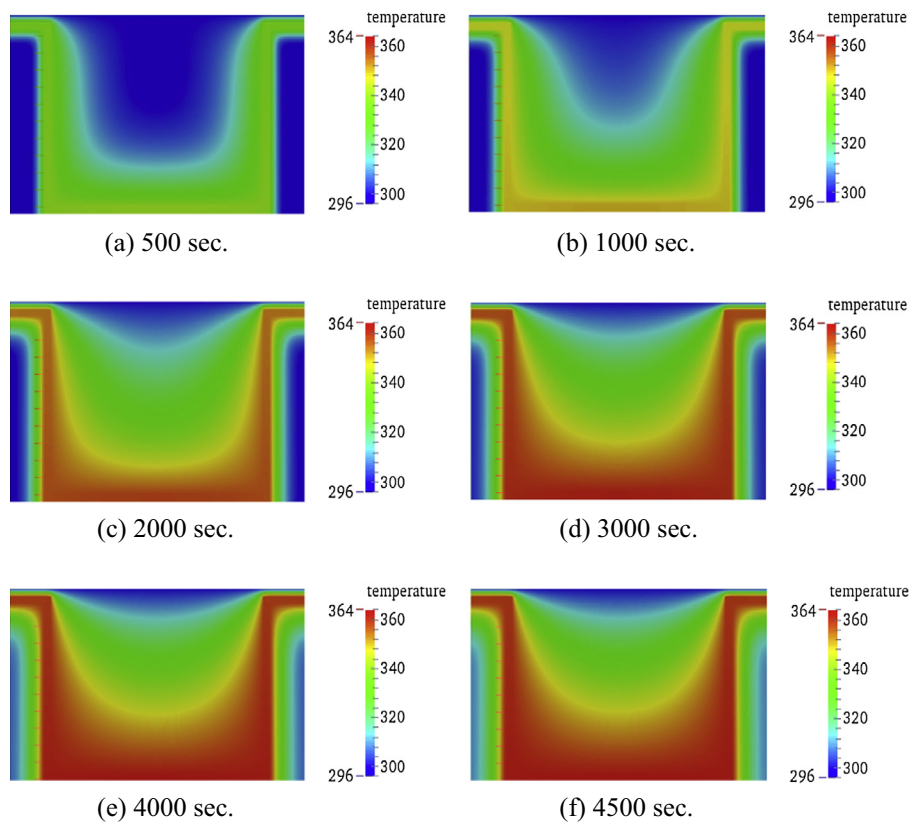


Fig. 8. Temperature distribution at different times for CF-20 + RT65/MWCNTs module.

is shown in Fig. 5. The figure shows good capability of the figure in predicting the trend of the module temperature response. Comparing Figs. 4 and 5 reveals that the increase in thermal conductivity of CF-20 + RT65/MWCNTs modules leads to a 7.8% reduction in the module surface temperature.

4. Results and discussion

4.1. Isotherms analysis

The temperature distributions in whole composite module for different times are presented in Figs. 6–8 for pure CF-20, CF-20 + RT65, and CF-20 + RT65/MWCNTs modules, respectively. The figures show the temperature distribution during 4500 s in a time

step of 500 s. It can be observed that the temperatures in the aluminum walls develops much faster than the those of module core because of the low thermal conductivity of the carbon foam as compared to aluminum. The figures also show that the temperature levels of CF-20 + RT65/MWCNTs, CF-20 + RT65 and CF-20 modules is relatively low as compared to the other, respectively. This can be attributed to effect of the presence of the phase change materials and the thermal conductivity enhancer (nano carbon tubes) in CF-20 + RT65 and CF-20 + RT65/MWCNTs modules which increase the overall heat capacity and heat diffusion of the module and consequently decrease the temperature rise. The code prediction also show that the temperature development of CF-20 + RT65/MWCNTs and CF-20 modules is relatively faster than that of CF-20 + RT65 modules and this can be attributed to the reduction of the thermal conductivity of the carbon foam by the insertion of

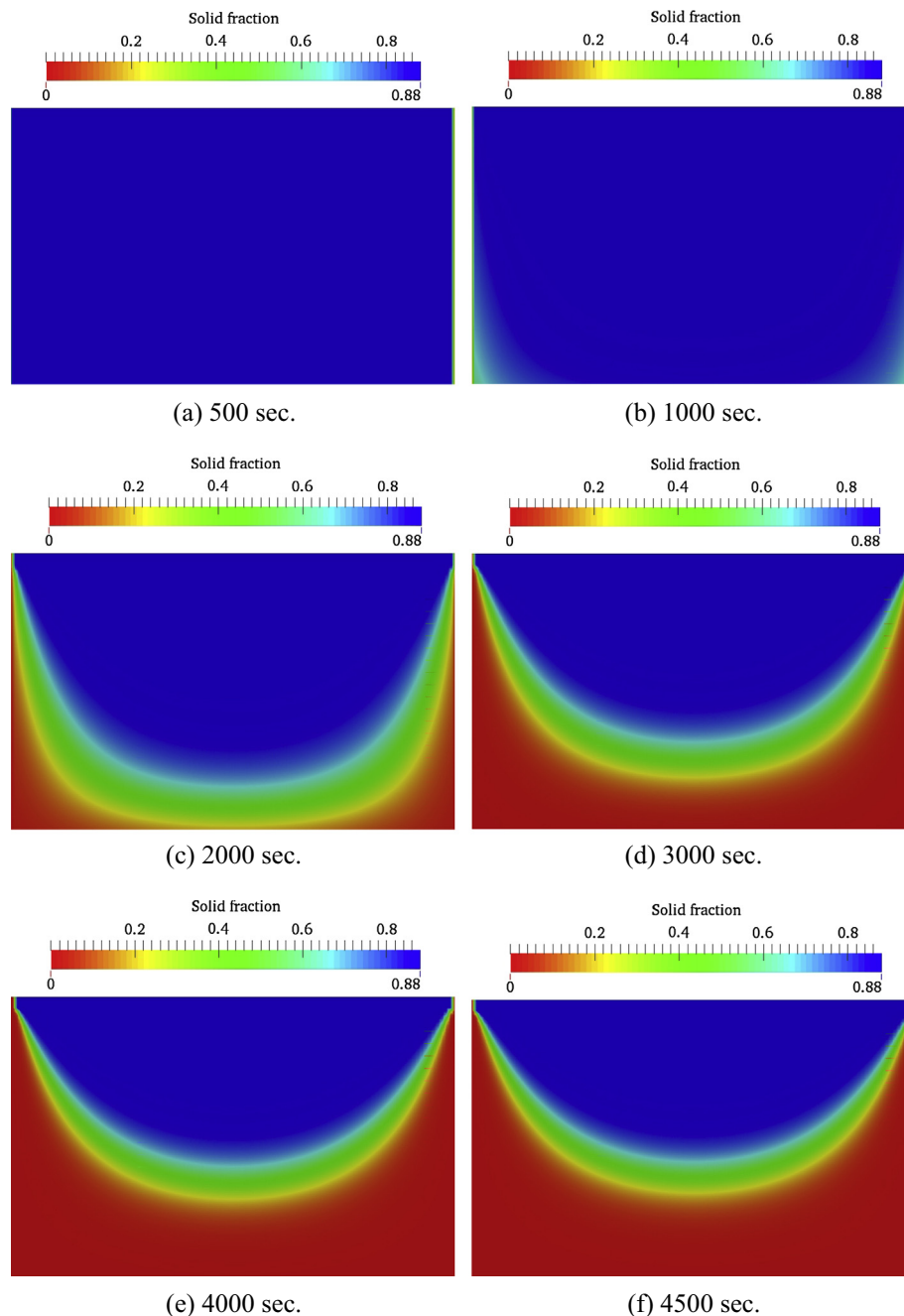


Fig. 9. Solid fraction versus time for CF-20 + RT65 module.

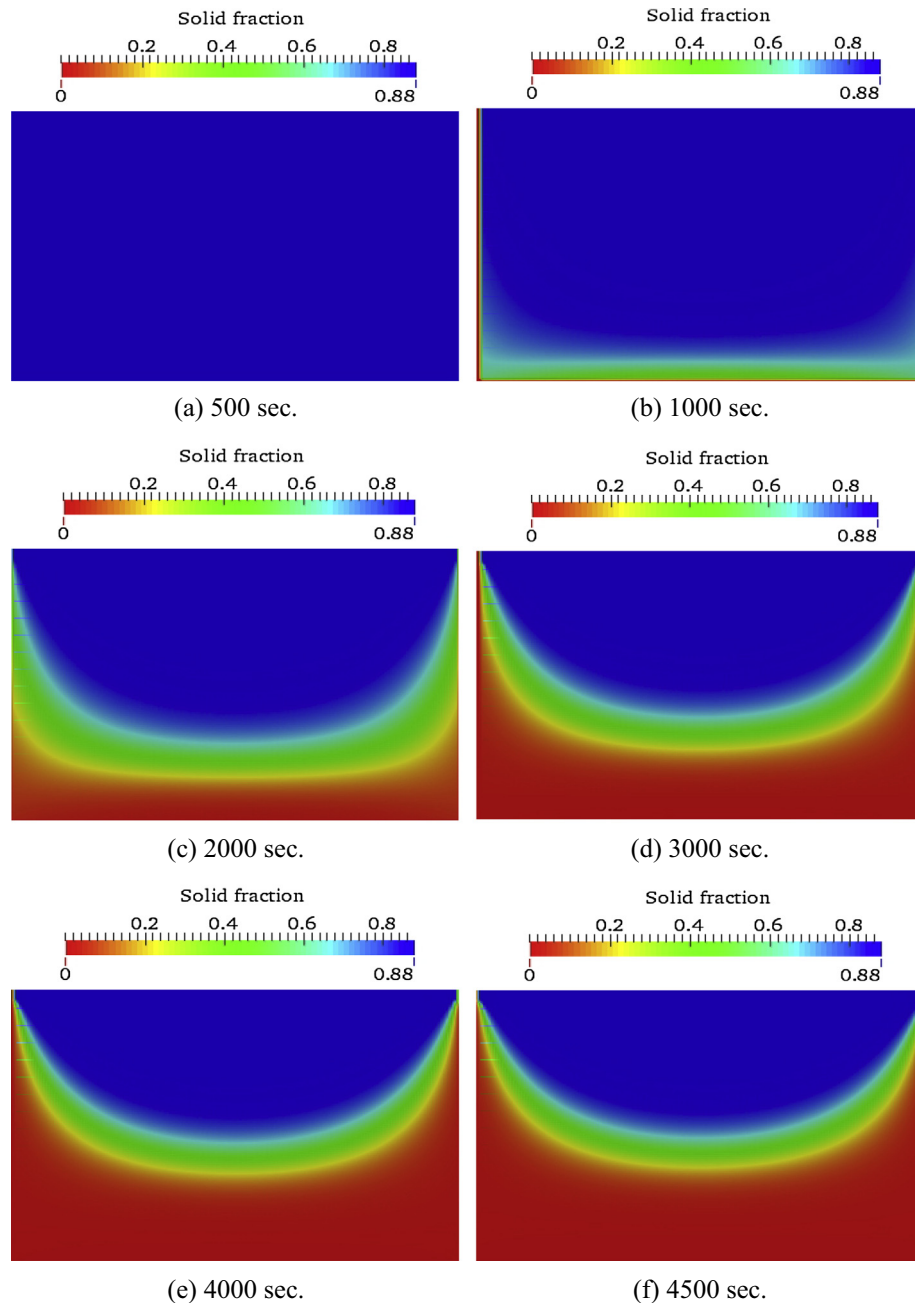


Fig. 10. Solid fraction versus time for CF-20 + RT65/MWCNTs module.

paraffin wax phase change material and the improvement of this thermal conductivity by the insertion of nano carbon tubes in the paraffin wax.

4.2. Melting front

The PCM whole melting process can be divided into three regions: solid, mush, and pure liquid. Figs. 9 and 10 show the solid fraction versus time inside CF-20 + RT65 and CF-20 + RT65/MWCNTs modules of 0.88 porosity, respectively during 4500 s in a time step of 500 s.

Starting at time $t = 0$, the temperature of active domain is held below the freezing temperature of RT65 where the temperature is 25 °C. The temperature of the bottom and side walls are still below the start of melting temperature of RT65 until reaching a

time of about 1000 s. Consequently, the PCM will start melting on the bottom and side walls and the solid front travels to the top. Colorized contours of the volume fraction of the PCM during melting at various time intervals have been shown. It should be mentioned that the color red is used to identify the liquid phase, whereas color blue is indicative of the frozen solid phase and in between is the mushy zone. The melt front at the container sides propagates faster since heat transfer from the aluminum walls is quite large than the composite core.

4.3. Modules temperature history

Model predictions for the transient temperatures histories at different depths in the modules are shown in Figs. 11–13 for CF-20, CF-20 + RT65 and CF20 + RT65/MWCNTs modules having

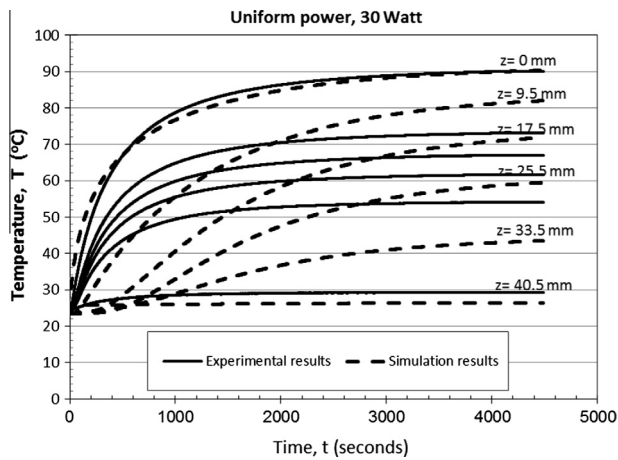


Fig. 11. Comparison of numerical and experimental results [32] of temperature at different depths (z) of pure CF-20 module.

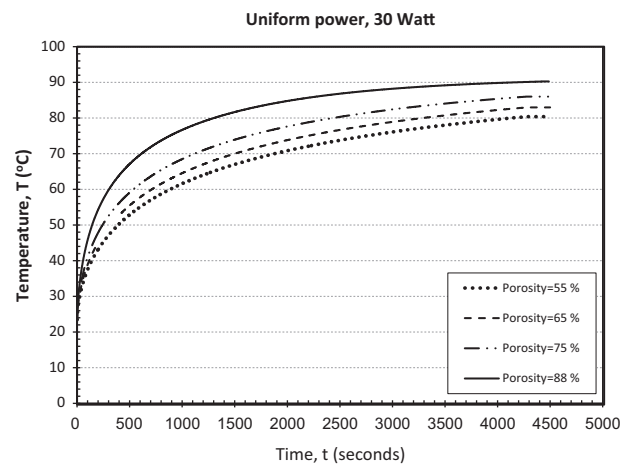


Fig. 14. Effect of carbon foam porosity on temperature history of CF-20 module.

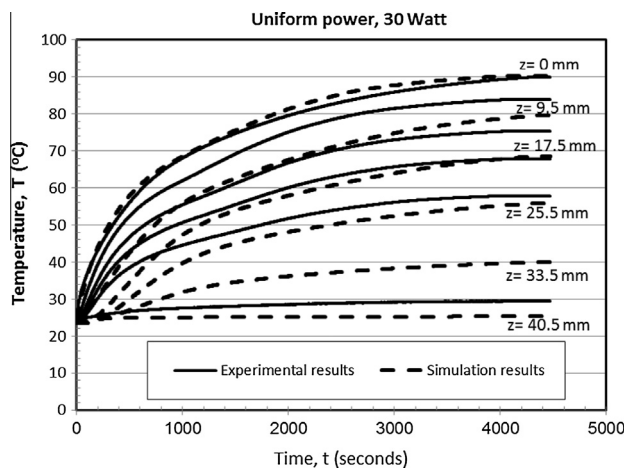


Fig. 12. Comparison of numerical and experimental results [32] of temperature at different depths (z) of CF-20 + RT65 module.

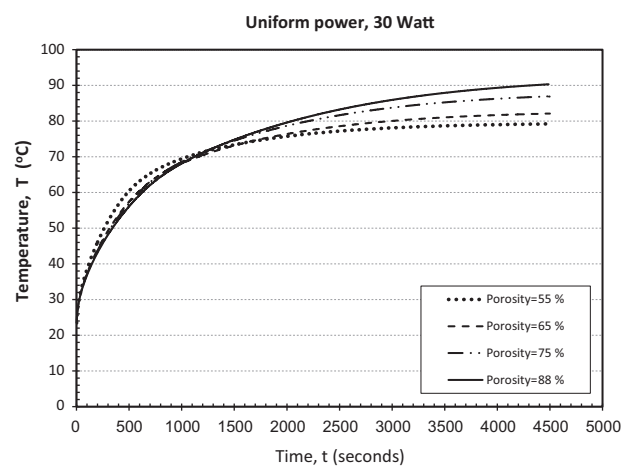


Fig. 15. Effect of carbon foam porosity on temperature history of CF-20 + RT65 module.

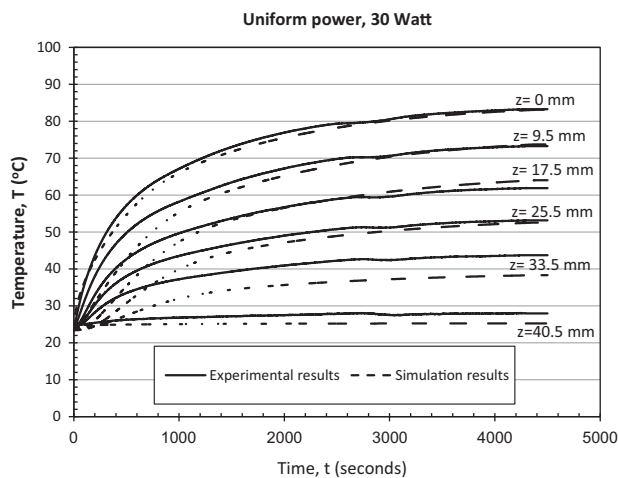


Fig. 13. Comparison of numerical and experimental results [32] of temperature at different depths (z) of CF-20 + RT65/MWCNTs module.

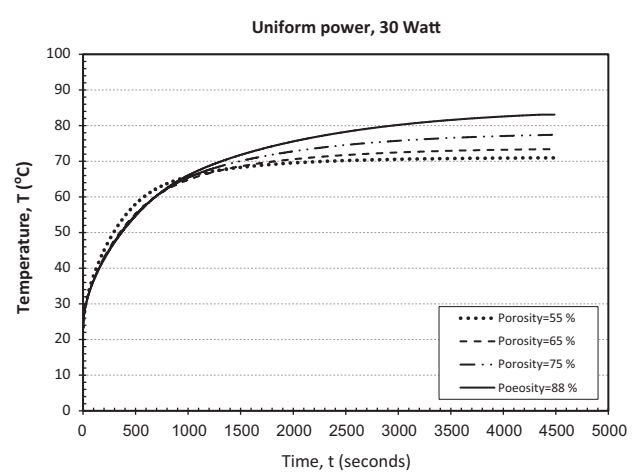


Fig. 16. Effect of carbon foam porosity on temperature history of CF-20 + RT65/CNTs module.

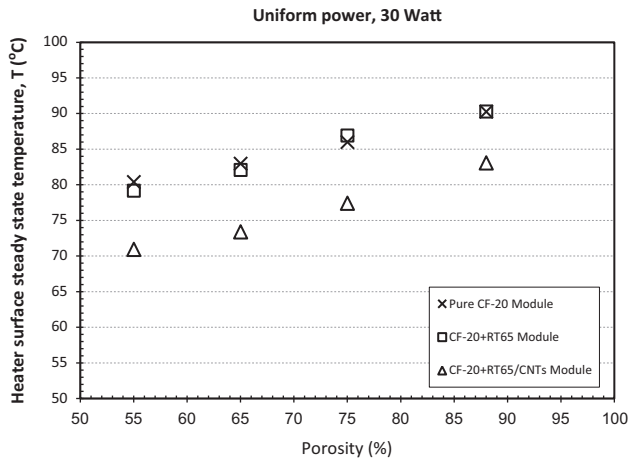


Fig. 17. Effect of porosity on module steady state surface temperature.

0.88 porosity, respectively. The experimental measurements obtained by Alshaer [32] for modules temperatures histories at the same depths are superimposed in Figs. 9 and 10 for the different modules. The figures shows that: (a) comparing the model predictions with the experimental data of Alshaer [32] reveals that the general behavior of temperature variation at different depths of all modules is well predicted by the numerical model, (b) the model predictions for modules surface temperature ($z = 0$) are with good numerical agreement with the experimental data of Alshaer [32], (c) as shown in Figs. 10 and 11, the models predictions for the temperature histories at different depths of CF-20 + RT65 and CF20 + RT65/MWCNTs modules agree with the experimental results of Alshaer [32], and (d) the experimental results of Alshaer [32], are relatively deviate from the model predictions for the temperature histories at different depths of CF-20 modules (see Fig. 11). This deviation can be attributed to the uncertainty in the position and contacts of thermocouples in the experimental study of Alshaer [32]. It may happen that the thermocouple probe is not in perfect contact with the solid structure of pure CF-20 as the probe may lay in the void structure (see Fig. 1). The deviation between the model prediction and the experimental data of Alshaer [32] were eliminated for CF-20 + RT65 and CF20 + RT65/MWCNTs as the inclusion of PCM and MWCNTs composites in the carbon foam pores assure good contact of the thermocouples probe with the solid structure of the modules eliminating the uncertainties of temperature measurements of Alshaer [32].

4.4. Effect of porosity

The results presented in the previous sections are for a specified value of porosity (0.88). Porosity is the most effective governing parameter of the proposed system. So, to generalize the results and study the effect of pure carbon porosity on the thermal behavior of the modules, program was run at different values of carbon foam porosities; namely 55%, 65%, 75% and 88% for CF-20, CF-20 + RT65 and CF20 + RT65/MWCNTs modules, respectively. Figs. 14–16 show the temperature history of the module surface for CF-20, CF-20 + RT65 and CF20 + RT65/MWCNTs, respectively. Fig. 14 shows the increase of the module surface temperature with the increase of the porosity of the pure carbon foam. This can be attributed to the decrease of the effective thermal conductivity of the carbon foam with the increase of its porosity. Decreasing effective thermal conductivity decreases heat transfer rate which results in increasing module surface temperature. For CF-20 + RT65 and CF-20 + RT65/MWCNTs modules, Figs. 15 and 16 show that in the first time interval ($t < 1250$ s for CF-20 + RT65

and $t < 1000$ for CF-20 + RT65/MWCNTs modules) the module surface temperature decrease with the increase of porosity that filled with RT65 or RT65/MWCNTs after then ($t > 1250$ for CF-20 + RT65 and $t > 1000$ for CF-20 + RT65/MWCNTs module) the module surface temperature increases with the increase of the porosity. This can be attributed to that in the first time interval ($t < 1250$ s for CF-20 + RT65 and $t < 1000$ for CF-20 + RT65/MWCNTs module) RT65 is still in the phase change process so most of the released heat is utilized in phase change and consequently reducing heat responsible on temperature rise which leads to lower module temperature. However after ($t > 1250$ for CF-20 + RT65 and $t > 1000$ for CF-20 + RT65/MWCNTs module) all of RT65 is already melted and the amount of heat diffusion increases and this consequently increase the module surface temperature. Increasing the porosity which is filled with RT65 liquid in this time interval ($t > 1250$ for CF-20 + RT65 and $t > 1000$ for CF-20 + RT65/MWCNTs module) decreases the effective thermal conductivity of the modules and this clarify the increase of the module surface temperature with increasing porosity. The point of inflection in the trend of CF-20 + RT65/MWCNTs module ($t = 1000$ s) is faster than that of CF-20 + RT65 module due to the enhancement of the thermal conductivity of the module by adding MWCNTs.

Fig. 17 shows the effect of porosity on the steady state temperature of the module surface for the three modules types. As shown in the figure, the steady state temperature increases with the increase of the porosity. This can be attributed to the decrease of thermal conductivity with the increase of the porosity which is filled with RT65 and RT65/MWCNTs in case of CF-20 + RT65 and CF-20 + RT65/MWCNTs modules. Fig. 17 also shows that the insertion of RT65/MWCNTs in CF-20 cause a reduction in the steady state temperature of module surface. The reduction is 11.25%, 11.63%, 11.49% and 8.33% in case of 55%, 65%, 75% and 88% porosities. This means that the reduction in the module surface temperature is approximately constant for porosities less than 75% and the reduction decreased for a porosity of 88%.

5. Conclusion

A numerical investigation is presented to predict the temperature histories of a thermal management modules for electronic equipment cooling using new composites of carbon foam, RT 65 phase change material (PCM) and Nano carbon tubes. Three different modules: pure CF-20, CF20 + RT65 and CF-20 + RT65/Nanocarbon modules are numerically tested to study the effect of insertion of RT65 and Nanocarbon tubes in the carbon foam of different porosities. The effect of carbon foam porosity is also studied. Mathematical model is obtained using the volume averaging technique based on single-domain energy equation and a control volume based numerical scheme. Interfacial effects influencing heat transfer process at the casing-composite junction and between the different surfaces within the composite have been addressed. Governing equations has been solved using a CFD code (Thétis, <http://thetis.enscbp.fr>). Mathematical model is validated by comparing its prediction with previous experimental measurements for pure CF-20 foam, CF-20 + RT65 and CF-20 + RT65/Nano carbon tubes composite modules. The model was used to predict the thermal characteristics of the different modules. Insertion of RT65 PCM in CF-20 carbon foam decreases the rate of temperature during the transient period. Results reveal that the increase in thermal conductivity of CF-20 + RT65/MWCNTs modules due to insertion of Nanocarbon tubes leads to a 11.5% reduction in the module surface temperature for carbon foam porosities less than 75%. The reduction decrease to 7.8% for a porosity of 88%. Numerical results of transient and steady state temperature histories at different depths

of modules were compared with previous experimental results for the different modules and fair agreement was obtained.

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