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Research Article

Cooling of Hot Obstacle Filled by PCM in Channel

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Abstract

A numerical study is conducted on the cooling of hot obstacle using a heat storage unit that is filled with phase change material (PCM) inside a rectangular channel with forced convection flow. The study is carried out for different thicknesses of phase change material and different heat fluxes. Also the effect of Reynolds number and Prandtl numbers changes on melting rate and mean temperature of hot obstacle are investigated The results are compared with case without PCM. The predicted results shows that the mean temperature of the hot obstacle stabilizes around melting point before the melting of whole PCM occurs and after that, its value that depends on the thickness of PCM and heat flux value, is comparable with the case without PCM.

Keywords*: Phase change material, Melting, Heat transfer, Forced convection.*

1. Introduction

Many studies have been carried out on the phase change materials over the last three decades. Phase change materials are very interesting due to their absorbing of large amount of energy as latent heat at a constant phase transition temperature. These materials can be used for passive heat storage. Major disadvantage of the PCM is related to their low thermal conductivity which impedes high rate of charging and discharging of heat flux. These types of materials have many useful properties including heat source at constant temperature, heat recovery with small temperature drop, high storage density, melting point which matches the application, low vapor pressure (1 bar) at the operational temperature, and chemical stability and non-corrosiveness. These properties allow the PCM to be used in many industrial applications such as thermal storage of solar energy (Alawadhi, 2009, Kamimoto et al. 1985 and Hadjieva et al, 1992) thermal management of electronic devices (Cabeza et al, 2002, Diarte et al, 2000 and Pal and Joshi, 1996), thermal storage in buildings (Koschenz and Lehmann, 2002 and Kissock et al, 1998), and engine cooling (Bellettre et al, 1997 and Vasiliev et al, 2000).

According to Telkes and Raymond (1949), the first study of phase change materials was carried out in the 1940s. There are few works reported until the 1970s. The first study on PCM was presented by Barkmann and Wessling (1975) for use in buildings, and later by other researchers (Hawes et al, 1993, Morikama et al, 1985 and Lee and Choi, 1998). Sokolov and Keizman (1991) presented applications of PCM in a solar collector for first time in 1991, and later by others, e.g. Rabin et al. (1995), Enibe (2002-1) and Einbe (2002-2) and Tey et al. (2002). Also, there are a few review papers on energy thermal storage and phase change material (Agyenim et al. 2010 and Farid et al, 2004). Following them, a beneficial review of thermal energy storage based on PCM was presented by Zalba et al. (2003). They classified types of PCM based on material properties, heat transfer and its applications.

In recent years, researchers have shown great interest in the application of PCM because of greenhouse gas emission and increasing cost of fossil fuels. Majority of the experimental and numerical studies are related to saving of energy in building structures and solar collectors. Khodadadi and Zhang (2001) studied the effect of buoyancy-driven convection on constrained melting of PCM in a spherical unit numerically. Their results showed the rate of melting at the top region of sphere is faster than at the bottom region due to increase conduction.

Kandasamy et al. (2008) investigated experimentally and numerically the use of PCM-based heat sink in transient thermal management of plastic quad flat package electronic devices. Tan and Tso (2004) experimentally studied the cooling of mobile electronic devices using a heat storage unit filled with n-eicosane inside the unit and found that the effectiveness of the device depended on the amount of PCM used.

Tan and Leong (1990) carried out an experimental study of solidification of pure n-Octadecane within two rectangular cells with different aspect ratios and three different constant heat fluxes. Their results showed that a faster rate of solidification occurred at higher heat rates and smaller aspect ratios. Hosseinizadeh et al. (2010) investigated both experimental and numerical study of constrained and unconstrained melting in a spherical unit using n-Octadecane as PCM that was initially subcooled to 1 °C. Alawadhi (2009) carried out a numerical study on

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transient laminar flow past an in-line cylinders array containing phase change material (PCM) using the finite-element method. He investigated a parametric study of heat exchanges between the PCM and flow at different Reynolds numbers and pitch to diameter ratios whereas Prandtl number was fixed at 0.71. His predicted results show that the Reynolds number has a significant effect on the PCM melting time, whereas the pitch to diameter ratio has an insignificant effect. Bagheri et al. (2010) studied the transient behavior of a thermal storage module numerically. The module is composed of a concentric tube, in which the annulus contains the phase-change material (PCM) and the inner tube carries the heat transfer fluid. They used three different PCM. They measured the charging time for every PCM at the same condition. The objective of this work is to investigate numerically the cooling of obstacle with constant heat flux using phase change material and forced convection flow in a rectangular channel.

2. Governing Equations

In the numerical study, the flow is considered unsteady, laminar, incompressible and two-dimensional. The viscous dissipation term is considered negligible. The viscous incompressible flow and the temperature distribution are solved using the Navier–Stokes and thermal energy equations, respectively. Consequently, the continuity, momentum, and thermal energy equations can be expressed as follows:

Continuity:

$$\boldsymbol{\partial_t(\rho) + \partial_i(\rho u_i) = 0} \quad (1)$$

Momentum:

$$\boldsymbol{\partial_t(\rho u_i) + \partial_j(\rho u_i u_j) = \mu \partial_{jj} u_i - \partial_i P + \rho g_i + S_i} \quad (2)$$

Energy:

$$\boldsymbol{\partial_t(\rho h) + \partial_t(\rho \Delta h) + \partial_i(\rho u_i h) = \partial_i(k \partial_i T)} \quad (3)$$

In these relations, u is the fluid velocity, ρ is the PCM’s density, μ is the dynamics viscosity, P is the pressure, g is the gravitational acceleration, k is the thermal conductivity and h is the sensible enthalpy which is defined as follows:

$$\boldsymbol{h = h_{ref} + \int_{T_{reff}}^{T} C_p \, dT} \quad (4)$$

The enthalpy, H is therefore:

$$\boldsymbol{H = h + \Delta h} \quad (5)$$

Δh is the latent heat content that may vary between zero (solid) and Lf (liquid), the latent heat of the PCM. Therefore, liquid fraction λ can be defined as follows:

$$\boldsymbol{\lambda} = \begin{cases} \boldsymbol{\Delta H / L_f = 0} & \boldsymbol{T < T_0} \\ \boldsymbol{\Delta H / L_f = 1} & \boldsymbol{T > T_l} \\ \boldsymbol{\Delta H / L_f = \frac{T - T_s}{T_l - T_s}} & \boldsymbol{T_l < T < T_0} \end{cases} \quad (6)$$

In Eq. (2), S is the Darcy’s law damping terms (as source term) that are added to the momentum equation due to phase change effect on convection. It is defined as follows:

$$\boldsymbol{S_i = \frac{C(1-\lambda)^2}{\lambda^3}} \quad (7)$$

The coefficient C is a mushy zone constant which is fixed at a value of 10^5 (kg/m3s) for the present study (Assis et al, 1988).

3. Numerical Procedure

Numerical solution of the present problem is solved using the commercial software Fluent 6.3. The computational domain of the model is shown in Figure 1. The domain has two regions: heat transfer fluid (HTF) region with height of *ha* and length of *L* and PCM region with height of *hp* and length of *Lp (Lp=ha).* Constant heat flux is applied to the bottom wall of PCM unit. The thermal conductivity and the thickness of PCM s bottom wall (heat storage unit) is *400* and *1.5* (mm), respectively. The temperature of cold air at inlet is fixed *26°C*, respectively. n-Octadecane is selected as PCM that its thermo-physical properties are taken in table 1. PCM is sub-cooled by *2 °C*.

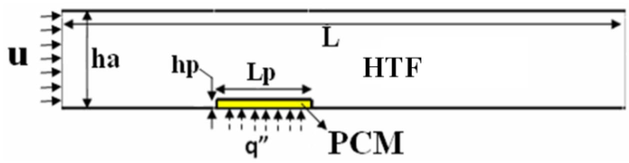


Fig. 1. Schematic of computational domain

In order to solve the momentum and energy equations, the power law differencing scheme and the SIMPLE method for pressure-velocity coupling are used. Also the PRESTO scheme is adopted for the pressure correction equation. The under-relaxation factors for the velocity components, pressure correction, thermal energy and liquid fraction are 0.2, 0.3, 1 and 0.9, respectively. Different grid sizes were selected and tested to ensure independency of solution from the adopted grid size based on comparison of melting fraction. An arrangement of 8,320 grids was found sufficient for the present numerical study. Adoption of fine grid distribution allows the use of longer time steps. The time duration to achieve the full melting is a good indicator of time step dependency. For case of hp=0.25 cm and q"=1000 w/m2, the PCM melted after 27.5,28.2 and 31.9 minutes with time step increments of 0.002, 0.005 and 0.01 seconds, respectively. Therefore, the time step is set 0.005 seconds. The number of iterations for every time step fixed at 40 was found sufficient to satisfy the convergence criteria (10-5). To validate, a comparison is done between present study and Assis et al. (2007) work for melting of RT27 (Rubitherm GmbH) in a sphere. The liquid fractions for experimental finding and present numerical study are shown in figure 2. It can be seen that the present study has a good agreement with Assis et al. (2007) work.

4. Results and Discussion

Figure 3 shows the contour of liquid fraction at various time instants in PCM unit. It can be seen that the melting rate grows in the right side of PCM unit while the time progresses. It is due to effect of cold HTF in the channel that strikes to the left side of PCM unit (fig.4). Variation of Liquid fraction versus time for different heat flux values and hp of 0.25 cm is shown in figure 5.

Table 1: Properties of n-Octadecane

Property	Value
melting temperature	*28/30 °C*
Density(solid/liquid)	*814 / 772* kg/m^3
Kinematics Viscosity	5×10^{-6} m^2/s
Specific Heat(s/l)	*1990 / 2330 J/kg K*
Thermal Conductivity(s/l)	*0.35 / 0.1505 W/m K*
Latent Heat of Fusion	*241.3 kJ/kg*
Thermal Expansion Coefficient	*0.00091* K^{-1}

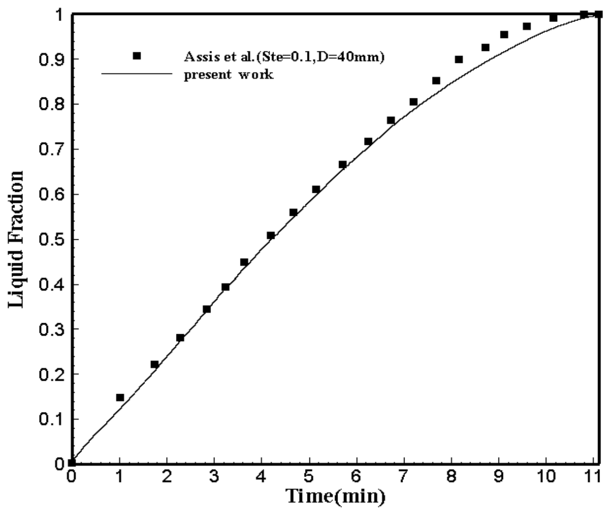
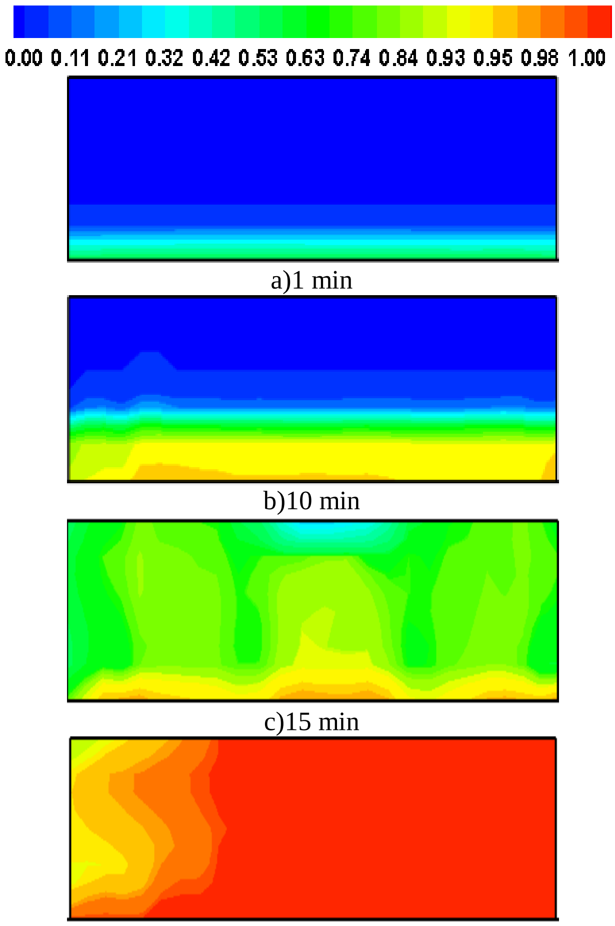


Fig. 2. Comparison of variation of liquid fraction between present study and Assis et al.

It reveals that liquid fraction versus time has a nonlinear relation with heat flux whereas full melting of PCM occurs after 14, 28 and 58 minutes for heat flux values of 1500, 1000 and 500 (w/m2), respectively. Figure 6 illustrates a comparison between mean temperature of hot obstacle for the case with and without PCM unit at different heat flux values. For the case with PCM, the mean temperature of obstacle remained at melting temperature of PCM for several minutes. It depends on the value of heat flux because of the high latent heat of PCM. After that it rises up to a constant temperature quickly when the whole of the PCM melted. It expected, after full melting of PCM, the temperature should had been higher than for case without PCM due to low thermal conductivity of PCM. But the natural convection in the melted PCM overcomes to this defect. Although the surfaces of heat transfer are extended with adding PCM unit (heat storage unit) over hot obstacle (similar to fin).

Variation of liquid fraction for different thicknesses of PCM is shown in figure 6. The melting duration of the whole PCM increases while PCM thickness increases. It is due to the total value of PCM latent heat (mL_f) and the areas of extensive surfaces are increased.

Figure *8* shows the effect of PCM thickness on the mean temperature of hot obstacle for constant heat flux of *1000* w/m^2. It can be seen that when the thickness of PCM increases, the mean temperature of hot obstacle remains for more time at low temperature.



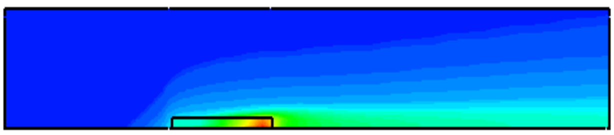
a)1 min

b)10 min

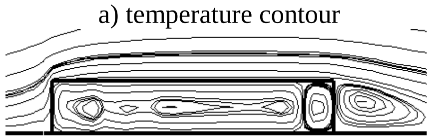
c)15 min

d)25 min

Fig. 3. Liquid Fraction contours for different time in the PCM unit.



a) temperature contour



b) streamlines

Fig. 4. Streamline and temperature contour for q"=1000 w/m2 and hp=0.25cm after 25 min

For instance, for *hp=0.5 cm*, it remains to *53* minutes in *302.15 K*. For *hp=0.125* and *hp=0.25 cm* the final mean temperature reaches to *353 K* and *376 K* whereas they are lower than *376 K* (mean temperature for case without PCM). For *hp=0.5 cm*, the final mean temperature of obstacle becomes greater than *376 K*. It seems that in the last case, the natural convection in the PCM zone and the extensive surfaces could not overcome to low thermal conductivity (thermal resistance increased with increasing of PCM thickness). The effect of HTF Reynolds change on liquid fraction and mean temperature of hot obstacle for $hp=0.25$ cm and $q''=1000\ w/m^2$ are shown in fig.9. The mean temperature of hot obstacle decreases extremely when Reynolds number (mass flow) of HTF increases. After full melting of PCM, it is lower than one for case without PCM in each Reynolds number. Also the difference between these two values decreases when Reynolds number increases. Change of HTF Prandtl number has significant effect on liquid fraction and mean temperature of hot obstacle whereas the whole of PCM don't melt for the Prandtl number of 6.2 (fig. 10a). Although, this is cause to the mean temperature of hot obstacle remains around melting point of PCM, but the figure 10b reveals that the mean temperature of hot obstacle for HTF prandtl of 6.2 is higher than in case without PCM unit. Therefore, it can be concluded that the adding of heat storage unit (filled with PCM) appropriates for HTF flow with low Prandtl number.

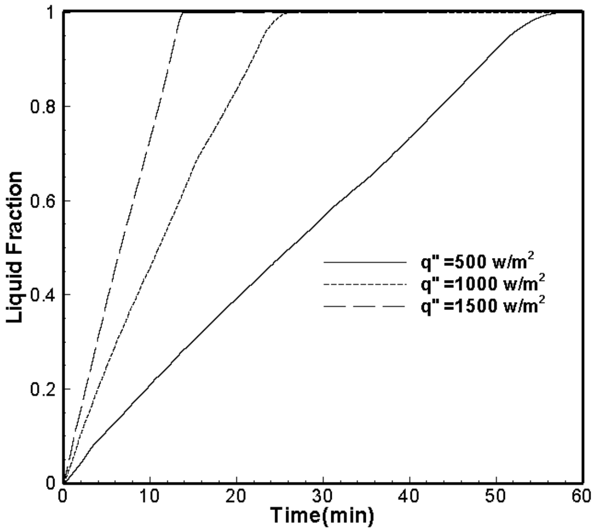


Fig. 5. Variation of liquid fraction for different heat flux for *hp=0.25 cm (Re=800, Pr=0.7)*

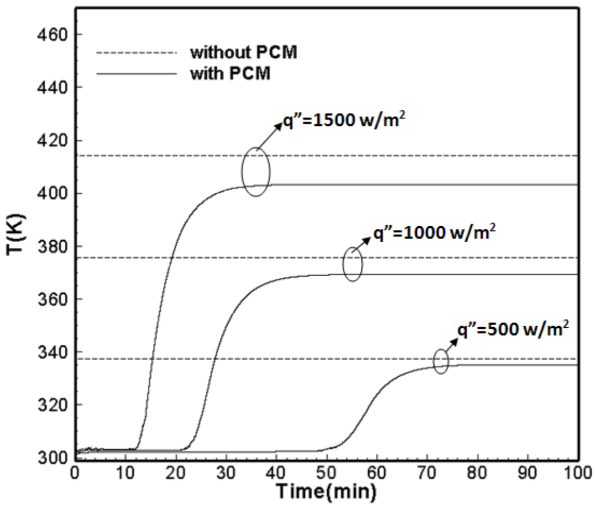


Fig 6. Mean temperature on hot surface for case with PCM and without PCM, *(Re=800, Pr=0.7, hp=0.25 cm)*

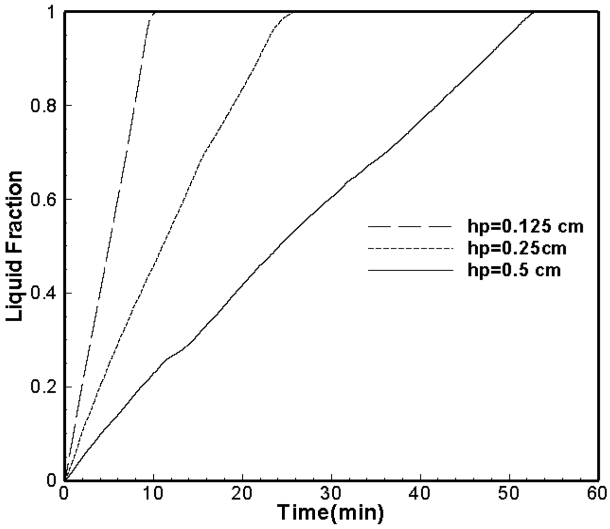


Fig 7. Variation of liquid fraction for different height of PCM, *($q''=1000\ w/m^2$, Re=800, Pr=0.7)*

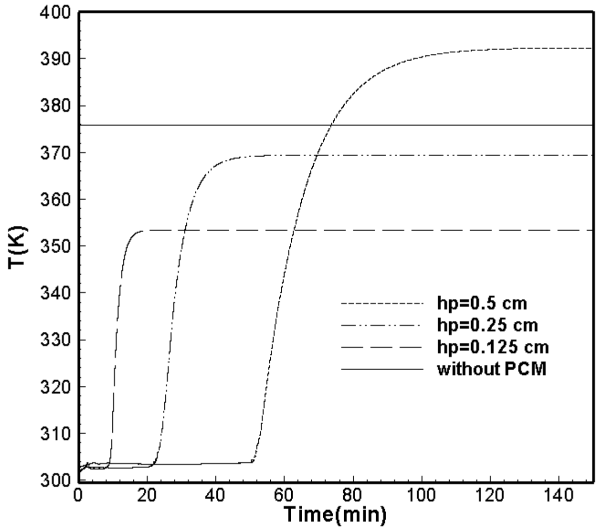
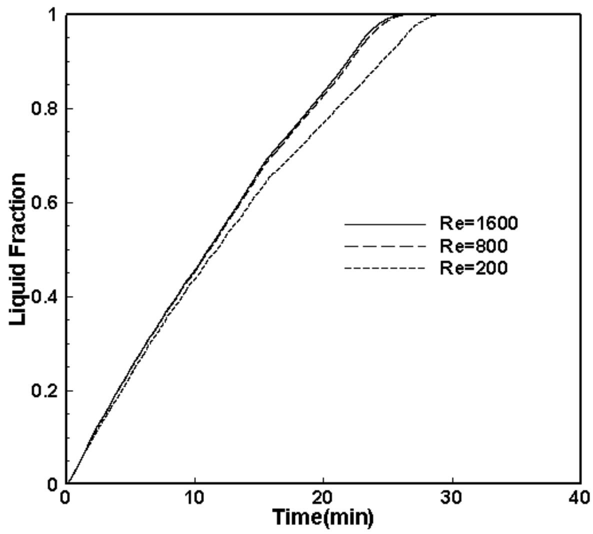
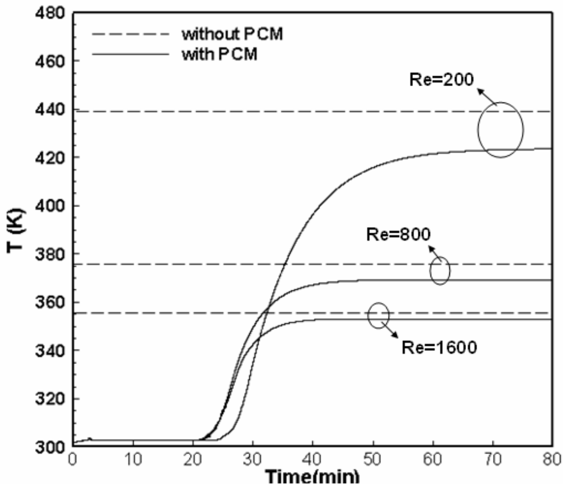


Fig 8. Distribution of mean temperature for case with different height of PCM and without PCM, *($q''=1000\ w/m^2$, Re=800, Pr=0.7)*

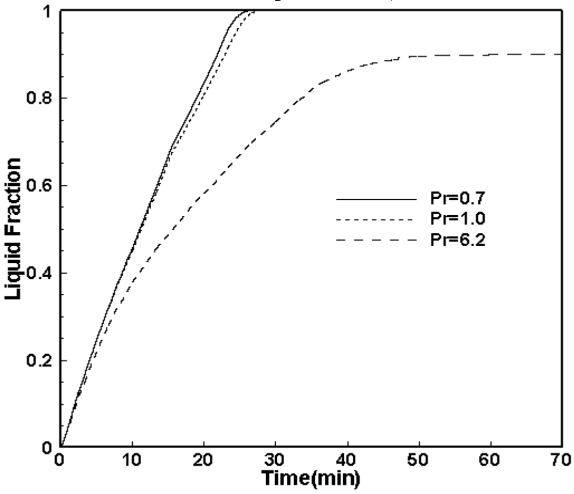


(a)

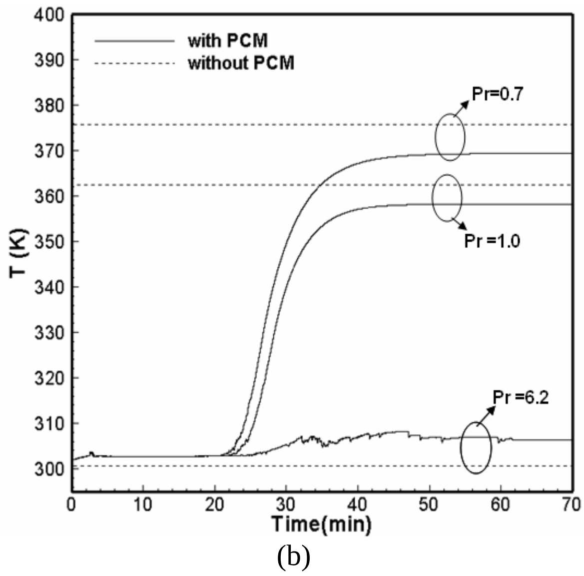


(b)

Fig 9. Variation of liquid fraction and mean temperature for different Reynolds number of HTF, *(q"=1000 w/m^2, Pr=0.7, hp=0.25 cm)*



(a)



(b)

Fig 9. Variation of liquid fraction and mean temperature for different Prandtl numbers of HTF, *(q"=1000 w/m^2, Re=800, hp=0.25 cm)*

5. Conclusion

In the present work, the effect of heat storage unit in the cooling of hot obstacle inside a rectangular channel with forced convection flow is studied. This study reveals that the PCM thickness, heat flux value, Reynolds number and Prandtl number of HTF have key roles in the melting rate and mean temperature of hot obstacle. The predicted results show the use of PCM as heat sink can stabilize the mean temperature of obstacle lower than specific temperature. Although after full melting of PCM, the mean temperature of obstacle rises sharply, but it can be appropriate in comparison with the case without PCM when HTF has low prandtl number.

References

Agyenim F., Hewitt N., Eames P., Smyth M., 2010, A review of materials, heat transfer and phase change problem formulation for latent heat thermal energy storage systems (LHTESS), *Renewable and Sustainable Energy Reviews*, **14**, 615–628

Alawadhi E.M., 2009, Thermal analysis of transient laminar flow past an in-line cylinders array containing phase change material, *Proc. IMechE, Part A: Journal of Power and Energy*, **223(4)**, 349-360

Assis E., Katsman L., Ziskind G. Letan R., 2007, Numerical and experimental study of melting in a spherical shell, *Int. J. Heat Mass Transfer*, **50**, 1790–1804.

Bagheri G.H., Mehrabian M.A., Hooman K., 2010, Numerical study of the transient behaviour of a thermal storage module containing phase-change material, *Proc. IMechE, Part A: Journal of Power and Energy*, **224(4)**, 349-360

Barkmann H.G., Wessling F.C., 1975, Use of buildings structural components for thermal storage, *Proceedings of the Workshop on Solar Energy Storage Subsystems for the Heating and Cooling of Buildings*, Charlottesville (Virginia), USA

Bellettre J., Sartre V., Biais F., Lallemand A., 1997, Transient state study of electric motor heating and phase change solid–liquid cooling, *Applied Thermal Engineering*, **17(1)**, 17–31

Brent A.D., Voller V.R., Reid K.J., 1988, Enthalpy-Porosity Technique for Modeling Convection-Diffusion Phase Change-Application to the Melting of a Pure Metal, *Numerical Heat Transfer*, **13**, 297-318.

Cabeza L.F., Roca J., Nogues M., Zalba B., Marın J.M., 2002, Transportation and conservation of temperature sensitive materials with phase change materials: *state of the art, IEA ECES IA Annex 17 2nd Workshop*, Ljubljana, Slovenia

Cuevas-Diarte M.A., Calvet-Pallas T., Tamarit J.L., Oonk H.A.J., Mondieig D. and Haget Y., 2000, Nuevos materials termoajustables, *MundoCient_ıfico*, June

Enibe S.O., 2002, Parametric effects on the performance of a passive solar air heater with storage, *Proceedings of the World Renewable Energy Congress WII*, Cologne, Germany

Enibe S.O., 2002, Performance of a natural circulation air heating system with phase change material energy storage, *Renewable Energy*, **27**, 69–86

Farid M.M., Khudhair A.M., Razack S.A.K. and Al-Hallaj S., 2004, A review on phase change energy storage: materials and applications, *Energy Conversion and Management*, **45**, 1597–1615

Hadjieva M., Kanev S., Argirov J., 1992, Thermo physical properties of some paraffins applicable to thermal energy storage, Solar Energy Materials, **27**, 181–187

Hawes D.W., Feldman D., Banu D., 1993, Latent heat storage in building materials, *Energy Buildings*, **20**, 77–86

Hosseinizadeh S.F., Tan F.L., Khodadadi J.M., Rabienataj Darzi, A.A., 2010, Experimental and Numerical Investigation of Unconstrained Melting inside a Spherical Container, *7th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamic*, Antalya, Turkey

Kamimoto M., Abe Y., Sawata S., Tani T., Ozawa T., 1985, Latent heat storage unit using form-stable high density polyethylene for solar thermal applications, *Proceedings of the International Symposium on Thermal Application of Solar Energy*, Hakone (Kanagawa, Japan)

Kandasamy R., Wang X.Q., Mujumdar A.S., 2008, Transient cooling of electronics using phase change material (PCM)-based heat sinks, *Applied Thermal Engineering*, **28**, 1047–1057

Khodadadi J.M.,, Zhang Y., 2001, 2001, Effects of buoyancy-driven convection on melting within spherical containers, *Int. J. Heat Mass Transfer*, **44**, 1605-1618

Kissock J.K., Hannig J.M., Whitney T.I., Drake M.L., 1998 Testing and simulation of phase change wallboard for thermal storage in buildings, *Proceedings of 1998 International Solar Energy Conference*, pp. 45–52, New York, USA

Koschenz M., Lehmann B., 2002, Development of a thermally activated ceiling panel with PCM for application in lightweight and retrofitted buildings, Energy Buildings, **36** 567–578

Lane G.A., 1986, Solar Heat Storage: Latent Heat Material, vol. II, *Technology, CRC Press*, Florida

Lee C.H., Choi H.K., 1998, Crystalline Morphology in High Density Polyethylene/Paraffin Blend for Thermal Energy Storage, *Polymer Composites*, **19(6),** 704–708

Morikama Y., Suzuki H., Okagawa F., Kanki K., 1985, A development of building elements using PCM, *Proceedings of the International Symposium on Thermal Application of Solar Energy, Hakone (Kanagawa),* Japan

Pal D., Joshi Y., 1996 Application of phase change materials for passive thermal control of plastic quad flat packages: a computational study, *Numerical Heat Transfer* Part A, **30**, 19–34

Rabin Y., Bar-Niv I., Korin E., Mikic B., 1995, Integrated solar collector storage system based on a salt-hydrate phase change material, *Solar Energy*, **55**, 435–444

Sokolov M., Keizman Y., 1991, Performance indicators for solar pipes with phase change storage, *Solar Energy*, **47**, 339–346

Tan F.L., Leong K.C., 1990, Conjugate solidification inside a thick mold, *J. Materials Processing Technology*, **89**, 159–164

Tan F.L., Tso C.P., 2004, Cooling of mobile electronic devices using phase change materials, *Applied Thermal Engineering*, **24(2)**, 159–169

Telkes M., 1949, Raymond E., Storing solar heat in chemicals—a report on the Dover house, *Heat Vent*, **46(11)**, 80–86

Tey J., Fernandez R., Rosell J., Ibanez M., 2002, Solar collector with integrated storage and transparent insulation cover, *Proceedings of Eurosun, Bologna*, Italy

Vasiliev L.L., Burak V.S ., Kulakov A.G., Mishkinis D.A., Bohan P.V., 2000, Latent heat storage modules for preheating internal combustion engines: application to a bus petrol engine, *Applied Thermal Engineering*, **20**, 913–923

Zalba B., Marın J.M., Cabeza L.F. and Mehling H., 2003, Review on thermal energy storage with phase change: materials, heat transfer analysis and applications, *Applied Thermal Engineering*, **23**, 251–283