Heat Transfer in Porous Media With Slurry of Phase Change Materials

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Abstract

3-D laminar model of a rectangular porous channel with high thermal conductivity and constant wall heat flux is chosen to investigate the enhancement of heat transfer when used in conjunction with the phase change material slurry. Numerical simulations for various wall heat fluxes and inlet velocities are carried out. The slurry consists of microencapsulated octadecane (C18H38) and water. The heat transfer coefficient of the porous channel with pure water and with micro-encapsulated phase change material are calculated and compared. The effect of porosity and permeability of the porous medium on the heat transfer coefficient while using slurry of phase change material are studied. The results show that the heat transfer coefficient of the porous channel can improve by introducing phase change material slurry, but only under certain heat fluxes, inlet velocities, and porous media properties.

Keywords: Porous Media, Phase Change Material, Forced Convection Heat Transfer

1. INTRODUCTION

There is a growing need to develop systems with high rate of heat dissipation in many industrial products, including electronic cooling packages, air conditioning and refrigeration systems. Recently, particulate flow of phase-change materials has attracted attention for enhancing the heat transfer rate. Encapsulated phase-change materials are attractive due to their high energy storage density and small temperature variation during the heat transfer. There are various phase-change materials, e.g. paraffin, fibers, foams and composites which are developed to enhance thermal efficiency as coolants, when used in conjunction with other fluids [1–4].

Forced convective heat transfer enhancement with micro-encapsulated phase change material (MCPCM) slurries have been investigated experimentally and numerically [5–11]. These studies show that the heat transfer coefficients measured for MCPCM slurry are significantly higher than for those of single-phase fluid flow in laminar flow conditions. However, slurries of phase change materials carry two main disadvantages: their low thermal conductivity hinders heat transfer and the slurry form does not strongly take advantage of mixing effect. Therefore the use of PCM slurry is limited to high heat fluxes as the particles in the slurry melt away very quickly and the advantage of small temperature variation characteristic of phase change materials is lost.

Another approach for enhancing the heat transfer rate is using porous media. Porous media increase the rate of heat transfer by their high thermal conductivity and by agitating the flow which improves local convection. Both numerical and experimental results show that the convective heat transfer is considerably enhanced by inserting porous medium in the flow channel [12–15]. The presence of the porous matrix has significant effect on the heat transfer and melting rate of the phase change

FIGURE 1: Schematic of domain for numerical simulations.

2.1 Phase Change Material Slurry

A mixture of water and octadecane paraffin ($C_{18}H_{38}$) is used as the micro-encapsulated PCM slurry. The inlet fluid temperature T_{in} is $298K$ which is below the melting range of octadecane $298 - 308$ K. Mass and energy balance equations [23] are used to calculate the density and specific heat of micro-encapsulated phase change material slurry.

$$\rho_b = \xi\rho_p + (1-\xi)\rho_f \tag{1}$$

$$c_b = \frac{\xi\rho_p c_p + (1-\xi)\rho_f c_f}{\rho_f} \tag{2}$$

Here, the properties for the shell are neglected since the encapsulation layer is assumed to be very thin and can be neglected in modeling. For calculating the suspension conductivity, Maxwell's [25] relation for the bulk thermal conductivity is used.

Manali Shukla & Fatemeh Hassanipour

$$k_b = k_f \frac{2 + \dfrac{k_p}{k_f} + 2\xi\left(\dfrac{k_p}{k_f} - 1\right)}{2 + \dfrac{k_p}{k_f} - \xi\left(\dfrac{k_p}{k_f} - 1\right)} \tag{3}$$

Representative values of the slurry properties obtained using the above equations for 15% microencapsulated octadecane paraffin are shown in Table 1.

	T<298°K	298°K<T<308°K	T>308°K
ρ_p (kg/m3)	850	-7T-2936	780
C_p (kJ/kgK)	1800	40T-10120	2200
K_p(W/mK)	0.31	-0.017+5.376	0.14
H (kJ/kg)		270	

TABLE 1: Properties of Octadecane Paraffin $C_{18}H_{38}$

The heat transfer process inside the phased-change filled particles is modeled using the following enthalpy based energy balance equation:

$$\frac{\partial}{\partial t}\left(\rho_p H\right) + \nabla\cdot\left(\rho_p u H\right) = \nabla\cdot\left(k_p \nabla T\right) \tag{4}$$

where the enthalpy H of the material is computed as the sum of the sensible enthalpy, E, and the latent heat, ΔH, where

$$\Delta H = \alpha L \tag{5}$$

α is a parameter to track the phase-change process inside the particle is the liquid fraction defined as:

$$\begin{aligned} \alpha &= 0 & T < T_{sol} \\ \alpha &= 1 & T > T_{liq} \\ \alpha &= \frac{T - T_{sol}}{T_{sol} - T_{liq}} & T_{sol} \le T \le T_{liq} \end{aligned} \tag{6}$$

The solution for the heat transfer process inside the particles is obtained using the energy balance Eq. 4 and the liquid fraction Eq. 5.

2.2 Porous Media
Porous Media is modeled using the local volume average of the mass, momentum and energy equations for an incompressible fluid flow through an isotropic, rigid, homogeneous porous medium confined within an impermeable wall by Brinkman-extended Darcy model [22]. In this model the thermo physical properties of the fluid and porous medium are constant. The volume average process is done by relating every point in the porous medium as a tiny volume *V* surrounded by a closed surface area of *A*. V_f *is* the fraction of volume *V* containing the fluid (10). When flow through a porous medium is involved, these equations are valid inside the pores in which some form of the macroscopic balance equations based on the volumetric element are employed.

The governing continuity, momentum and energy equations (7), (8), (9) for present work are:

$$\nabla \cdot \langle u \rangle = 0 \tag{7}$$

$$0 = -\nabla\left(\phi \cdot \langle P \rangle\right) + \mu_{eff} \cdot \nabla^2 \langle u \rangle - \frac{\mu_b}{K}\phi\langle u \rangle - C\rho_b\phi^2\langle u \rangle\langle u \rangle \tag{8}$$

$$\langle u \rangle \cdot \nabla\langle \rho_b c_b T \rangle = \frac{1}{\phi}\nabla \cdot \left(k_{eff} \cdot \nabla\langle T \rangle\right) \tag{9}$$

Where:

$$\langle P \rangle = \frac{1}{V}\int P.dV \tag{10}$$

$$\langle u \rangle = \frac{1}{V}\int u.dV \tag{11}$$

$$k_{eff} = \phi k_b + (1-\phi)k_s \tag{12}$$

$$\phi = \frac{A_f}{A_t} \tag{13}$$

A_f is the area occupied by the fluid and A is the total volume of the material. Parameters p, ρ, μ can be measured independently. However, μe, K and C depend on the geometry or the permeable medium and cannot be measured directly, nor calculated analytically, because there is no model relating them to more basic (measurable) quantities valid for all porous media. The Brinkman-Hazen-Dupuit-Darcy equation has an alternative form where C is replaced by $C f /K$. The constant C_f is often takes the value 0.55 (1/m).

$$C = \frac{C_f}{\sqrt{K}} \tag{14}$$

In this study the value of C is calculated by considering $10^{-8} m^2 < K < 10^{-2} m^2$.

To determine the heat transfer rate, a local heat transfer coefficient h_{loc} is defined as,

$$h_{loc} = \frac{q''}{T_s - T_{in}} \tag{15}$$

where T_s is the temperature along the heated surface and can be obtained by solving the above energy equations using the finite volume method. Therefore, an averaged heat transfer coefficient along the heated surface, is defined as

$$h = \frac{1}{A}\int h_{loc}dA \tag{16}$$

The mathematical formulation for the convection heat transfer problem considered here is solved by the finite-volume method with successive over-relaxation. The solver method is segregated and second-order accurate in space and time. An unstructured grid technique was adopted for

accelerating the convergence. Grid and time-step accuracies are established by varying the grid size and the time-step utilized in the simulations, considering the most stringent configuration considered here, namely maximum heat flux of 30kW/m2 and inlet flow velocity 0.03m/s, see Figures 2 and 3. As shown the data appear to be almost equivalent for the grid size of 0.25mm and 0.5mm and also for 0.25s and 0.5s. Based on this successive refinement, the time interval Δt = 0.5s and grid size ΔG = 0.5mm were chosen for the solution.

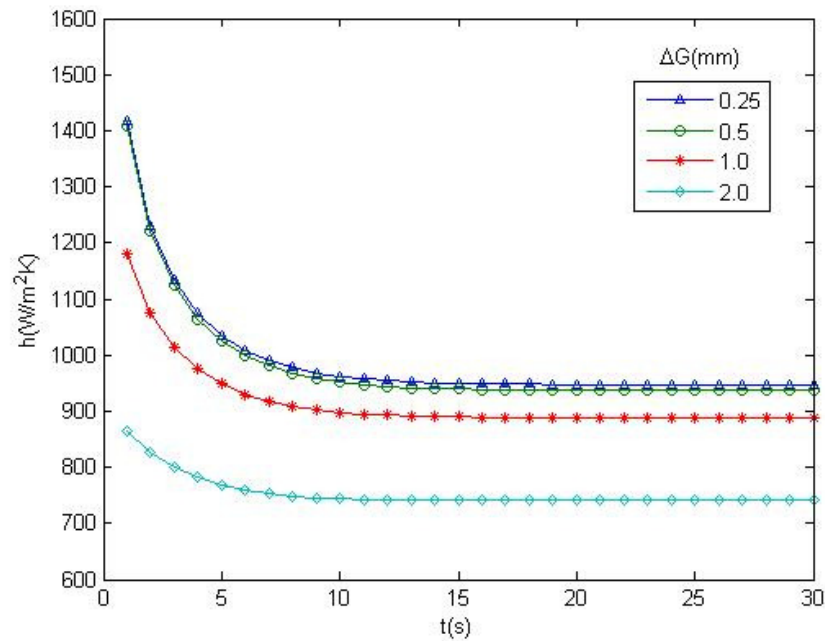**FIGURE 2:** Representative of time interval size accuracy test.

FIGURE 3: Representative of grid size accuracy test.

3. RESULTS

Heat transfer coefficients are compared for three cases: (1) pure water flow in a porous channel (h_p), (2) PCM slurry flow in non-porous channel (h_S), and finally (3) PCM slurry flow in a porous channel (h_{PS}). The values of heat transfer coefficients are obtained for three different heat fluxes of $q'' = 10kW/m2$, $30kW/m2$ and $50Kw/m2$ and three different velocities ranging from $u = 0.01m/s$ to $u = 0.05m/s$.

Figure 4 shows that between cases (1) water in porous media and (2) PCM slurry in non-porous media, the higher heat transfer coefficient occurs when pure water flows through a porous channel. To illustrate how the addition of PCM particles affects the heat transfer rate, we define a new parameter known as Δh that shows the difference between both heat transfer coefficients in porous media, that is, case (1) water in porous media, and case (3) PCM slurry through porous media:

$$\Delta h = h_{ps} - h_p \tag{17}$$

The variation in Δh over time is depicted for different heat fluxes and flow velocity values in Figures 5, 6, 7. Non-linear behavior of the heat transfer coefficient for PCM slurry in the first 30 seconds is caused by the phase change process inside the particles. For the remaining graphs, the results are shown exclusively for just the phase change intervals.
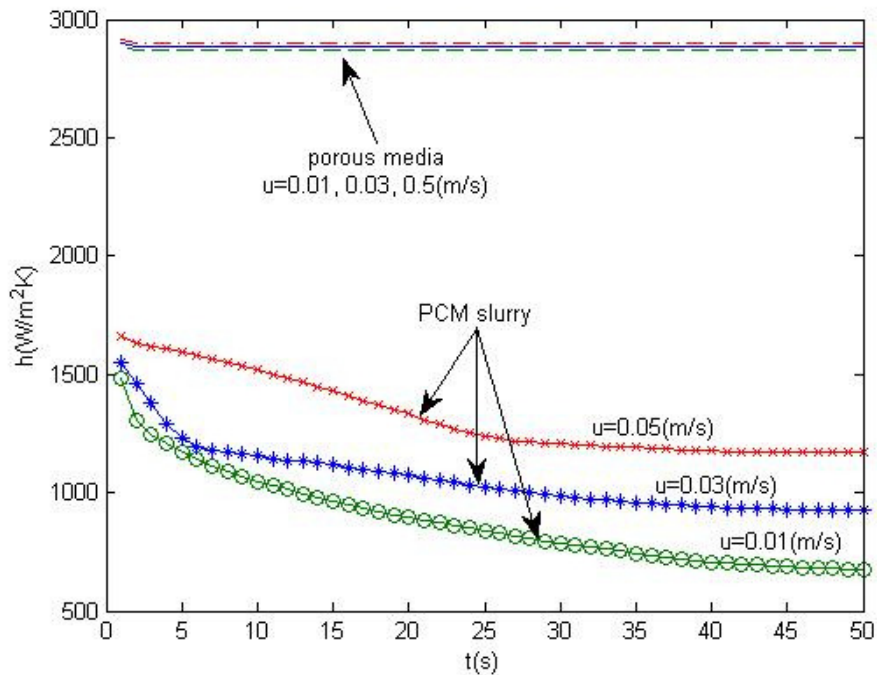

FIGURE 4: Heat transfer coefficient, water in porous media versus PCM slurry through porous media.

Figure 5 shows that for a low heat flux such as $q'' = 10kW/m2$, the heat transfer coefficient of phase change material slurry through porous channel is almost identical to that of pure water through porous channel because the slurry of phase change material has not fully melted. Effect of the velocity change for the same heat flux, is shown in Figure 5 and suggests no significant change in Δh even when the inlet flow velocity is increased. This result indicates the need of higher heat flux and inlet flow velocity to gain the advantage of slurry flow through porous media.

Figure 6 shows the variation of Δh over time for heat flux $30kW/m2$ at various flow velocities. Here, the heat transfer is more affected by the PCM particles due to the advantage of the melting process and the latent heat release. The heat transfer coefficients are better at high velocities which increases

the mixing effect in porous media. When velocity increases, the effect of latent heat and mixing effect become comparable.

To further illustrate the effect of PCM slurry through porous media in higher heat fluxes, the results are plotted at 50kW/m2 at various velocities in Figure 7. The results show significant increase in Δh, suggesting complete melting of PCM slurry in porous media. When velocity is low, particles have more time to melt completely and give up all their latent heat. By increasing the velocity, both mixing affects and latent heat of solid particles cause the enhancement of heat transfer rate (Figure7).
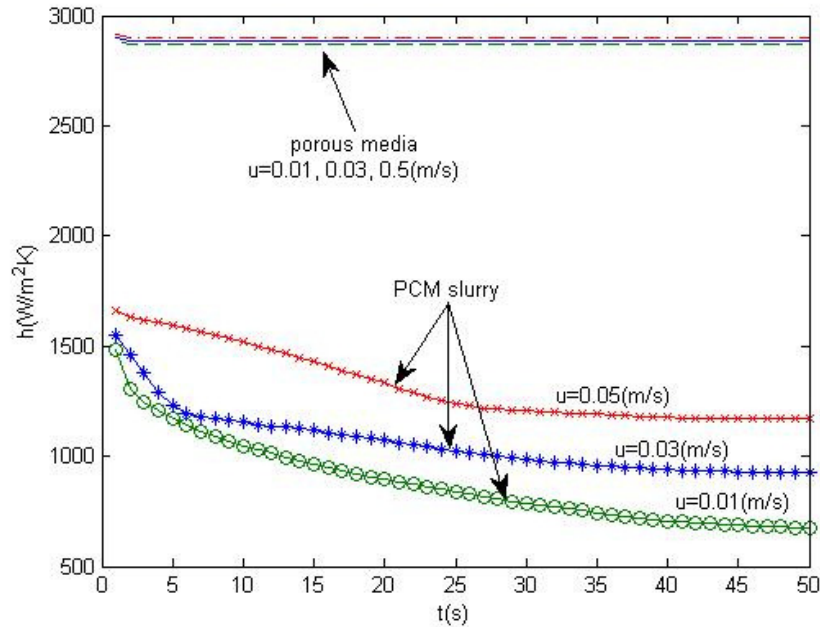

FIGURE 5: Effect of PCM addition to the flow in porous media on the heat transfer coefficient enhancement q"=10kW/m^2.

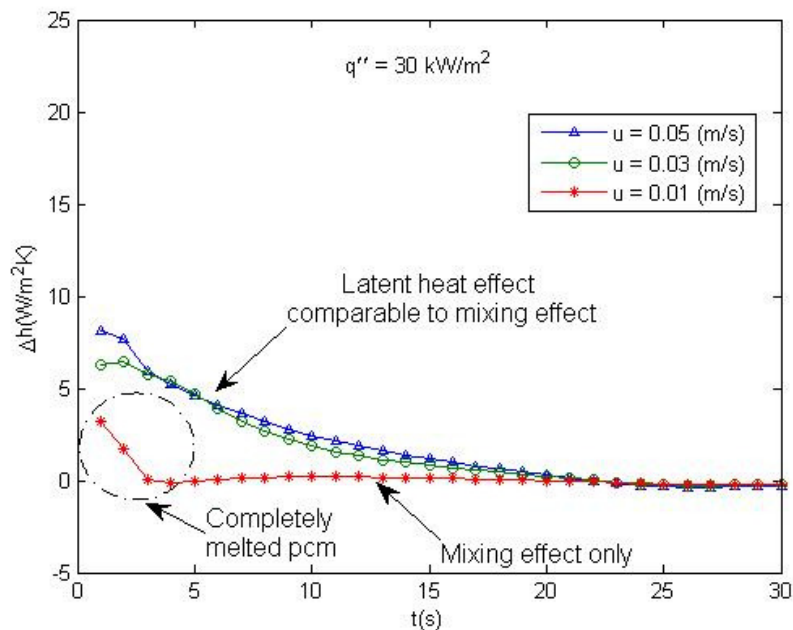**FIGURE 6:** Effect of PCM addition to the flow in porous media on the heat transfer coefficient enhancement q"=30kW/m^2.
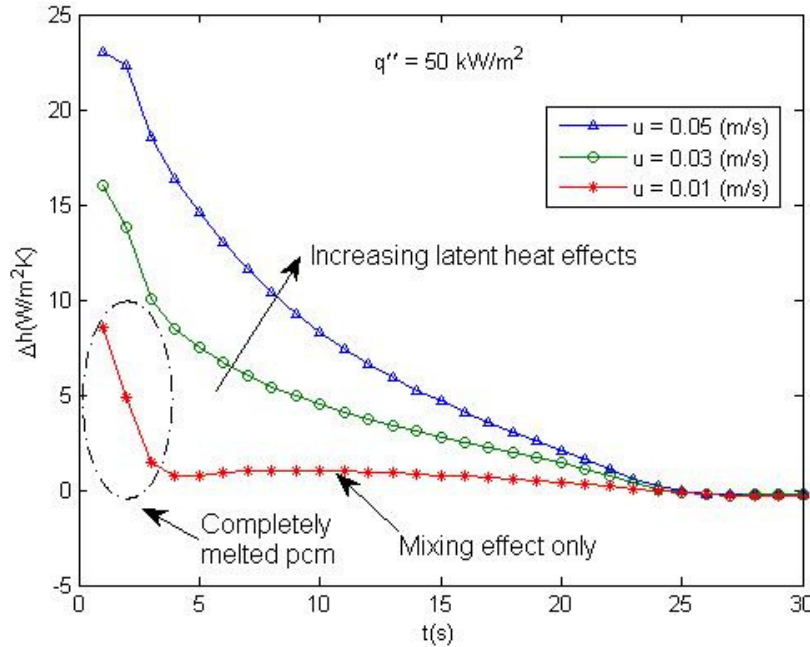

FIGURE 7: Effect of PCM addition to the flow in porous media on the heat transfer coefficient enhancement q"=50kW/m^2.

All the above results suggest that encapsulated phase-change material slurry flow through porous channel increases the heat transfer coefficient for specific ranges of heat flux and velocity.

The effect of porosity and permeability of the porous media on the heat transfer coefficient is also investigated. In this study, porosity is changed between 0.2 and 0.8 and the permeability from $10^{-2}m^2$ to $10^{-8}m^2$. Effect of porosity on the heat transfer coefficient can be seen in Figure 8. The results show that the heat transfer coefficient increases as the porosity decreases for the case of PCM slurry flowing through porous media. Although the coolant flow passes through the high pores channels more easily but the effect of high conductivity porous media structure is dominant in enhancing the heat transfer.

Figure 9 shows the heat transfer coefficient versus time for maximum and minimum porosity and permeability. The results indicate that porosity changes have the dominant effect on enhance- ment of heat transfer coefficient compared to the permeability. For the maximum porosity of 0.8, the initial values of heat transfer coefficients are higher for more permeable media. The reason is that for high porosity media, presence of more PCM slurry while flowing easily through porous media causes the heat transfer enhancement. After melting completion around 15 seconds, the heat transfer increases for lower permeability. The results for porosity of □ = 0.2 show very small changes in heat transfer coefficient, indicating less effect of PCM slurry at higher porosities, Figure 9.
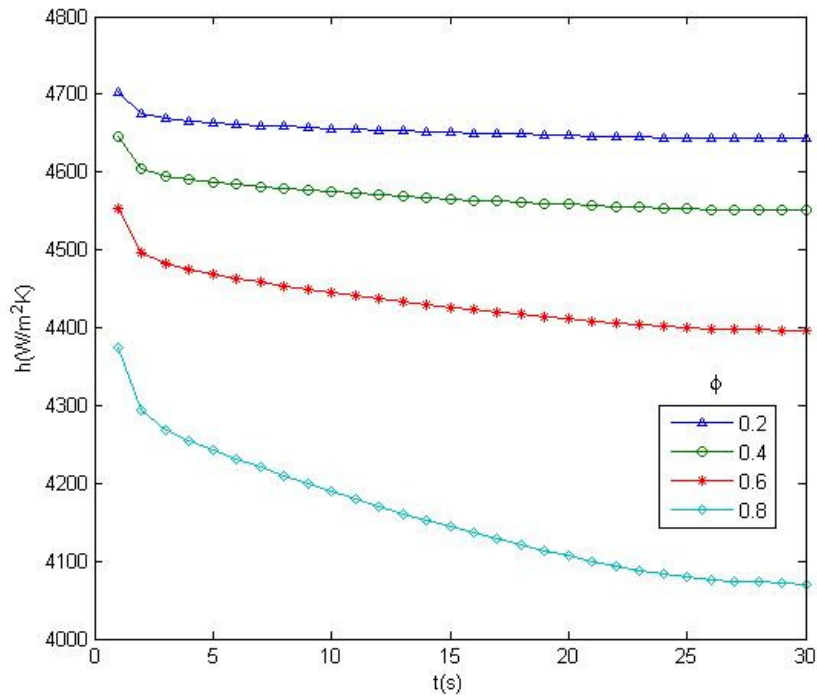
FIGUR 8: Effect of porosity on heat transfer coefficient at q''=50kW/m², u=0.05m/s and K=10⁻²(m²).

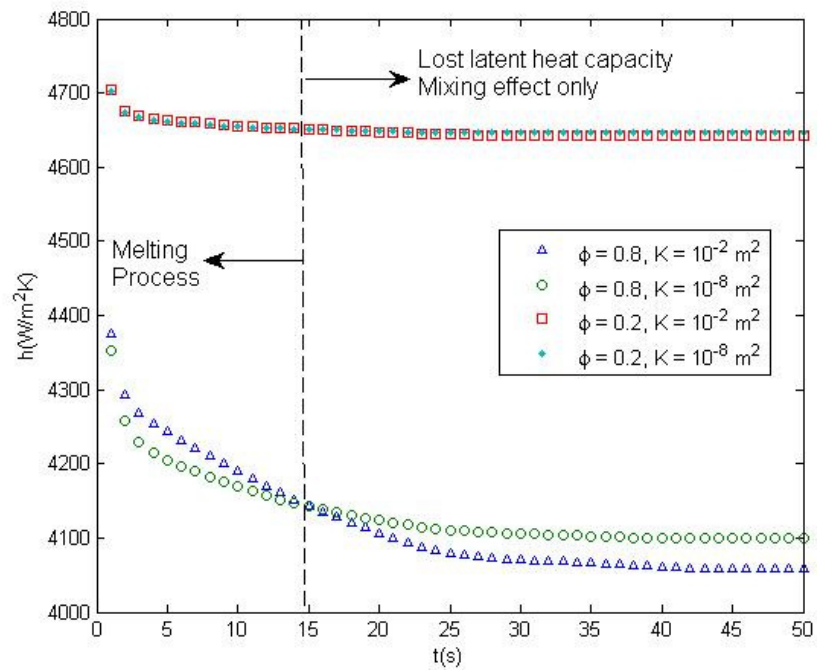**FIGURE 9:** Effect of permeability on heat transfer coefficient at q''=50kW/m², u=0.05m/s and Φ=0.8.

4. CONCLUSION

A brief summary of the present study is given below. When using phase change material slurry carrier through porous media:

1. At low heat fluxes, mixing effect by porous media has dominant effect on heat transfer rate compared to the latent heat affects of phase change materials.
2. At high heat fluxes, addition of phase change material particles to the flow in porous media is more beneficial for enhancing heat transfer rate.
3. PCM slurry through porous media with low porosity has the maximum heat transfer coefficient.
4. For low porosity media, the effect of permeability is negligible in term of contribution to the heat transfer rate.
5. For high porosity media, permeability affect on the enhancement of heat transfer rate.
6. Before melting process, higher permeable media enhances heat transfer coefficient. However, after melting process, low permeability media have better heat transfer rate.

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