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A TWO-TEMPERATURE MODEL FOR THE ANALYSIS OF THAWING HEAT TRANSFER OF ICE IN ALUMINUM FOAMS

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ABSTRACT

This study presents numerical results for ice thawing heat transfer in high porosity aluminum foams. A two-temperature model is used due to the big difference in thermal diffusivities between aluminum foams and ice/water. A general momentum equation which includes the Brinkman-Forchheimer extension to Darcy flow is employed when ice thawing. Apparent heat capacity method is used to simulate phase change heat transfer of ice thawing process in aluminum foams. The effect of aluminum foam's porosity in thawing process is studied. The simulation results shows that thawing time of ice filled with aluminum foams is greatly shorter than that without aluminum foams, and thawing time becomes longer with the increasing of aluminum foams porosity.

INTRODUCTION

Efficient and reliable thermal storage systems are an important requirement for many applications due to the non-coincidence of heat demand and supply or availability. The phase change energy storage has the advantages for their large heat storage capacity and their isothermal behavior during charging and discharging process. However, a negative aspect is that most of PCMs suffer from inherent low thermal conductivity. The use of finned tubes with different configurations had been proposed by various researchers as an efficient means to improve the heat transfer rate [1~5]. Cabeza [6] used three methods to enhance the heat transfer in a cold storage working with water/ice as PCM. The result indicated that a new PCM-graphite composite material showed an increase in heat flux bigger than with any of the other techniques. Experiments were carried out to investigate the methods of enhancing the thermal response of paraffin wax heat storage tubes by incorporating aluminum thermal conductivity promoters of various designs into body of the wax. It was found that the melting and solidifying times were reduced significantly due to these promoters [7]. In the past

NOMENCLATURE

c	[J/(kg·k)]	specific heat
C_D	[-]	inertial coefficient
d	[m]	particle diameter
Da	[-]	Darcy number
g	[m ² /s]	gravitational acceleration
h	[W/(m ³ ·k)]	volumetric heat transfer coefficient
H	[m]	height of enclosure
h_{ls}	[J/kg]	latent heat
K	[m ²]	permeability of the aluminum
L	[m]	length of enclosure
Nu	[-]	Nusselt number
P	[Pa]	pressure
Pr	[-]	Prandtl number
q	[W]	heat flux
Ra	[-]	Raleigh number
Re	[-]	Reynolds number
T	[K]	temperature
u	[m/s]	the velocity of x direction
v	[m/s]	the velocity of y direction
Special characters		
α	[K ⁻¹]	thermal expansion coefficient
ϵ	[-]	the porosity of aluminum foams
λ	[W/(m·k)]	thermal conductivity
ρ	[kg/m ³]	density
μ	[kg/(m·s)]	dynamic viscosity of water
τ	[s]	time
Subscripts		
eff		Volumetric effective expression
g		ice
$init$		initial
l		water
m		thawing point
s		aluminum foams

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twenty years, high porosity metal foam have received more attention and been applied in many new technologies. Thermal science field has paid more attention to the research on the metal foams and achieved many practical results [8].

In general, metal foams are mathematically modeled using the technique of volume-averaging owing to the complexity involved in modeling the metal foam and saturating fluid separately [9]. Amiri and Vafai [10, 11] used a semi-heuristic model to account for local thermal non equilibrium for steady and transient forced convective flows through a bed of spherical particles. They explored the importance of non-Darcian terms and thermal dispersion effects on thermal and flow characteristics. Error maps were introduced to quantify the results. The solid-to-fluid thermal conductivity ratio was found to have a profound influence on the local thermal equilibrium. Mohammed [12] performed a parametric study for natural in a porous enclosure under steady-state conditions. Phanikumar and Mahajan [13] reported experiments and numerical analysis of buoyancy induced flow in a high porosity metal foam block heated from below and surrounded on all other faces by fluid. Their results indicated that the thermal non-equilibrium model provided a superior description of heat transfer in metal foams. This paper presents a numerical solution based on a two-temperature model for the thawing of ice which filled with aluminum foams.

SCHMATIC AND NUMERICAL SOLUTION

Physics description

As shown in Fig.1.A aluminum foams (shown in Fig.2) saturated with fluid is contained in a square enclosure of side H. The left, right and bottom walls are adiabatic. The top wall is held at the constant heat flux q , which is 1000W constantly. It is assumed that aluminum foam saturated with phase change materials includes three different state zones as follows: solid zone, liquid-solid combined zone and liquid zone. The practical heat transfer process of liquid zone considers both phase change heat conduction and natural convection. This natural convection occurs due to temperature difference. In developing a two-temperature model of phase change process in aluminum foam, the assumptions are assumed as follows:

(1) Aluminum foams is isotropic.

(2) In single phase region, physical properties are temperature independent and in solid-liquid region, the physical properties are basically linear with temperature.

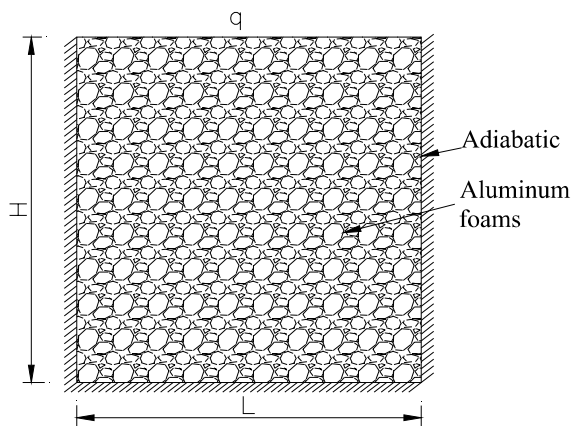


Figure 1 Schematic diagram of problem considered

(3) Surface tension and curvature effects at the interface are assumed insignificant.

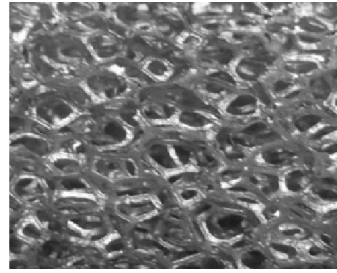


Figure 2 Aluminum foams

Mathematical formulation and numerical model

It is assumed that there is no viscous dissipation, the gravity acts in vertical direction. The momentum equations include the Brinkman's term and Forchheimer's extension to Darcy flow.

Continuity equation:

$$\frac{\partial(\rho_l u)}{\partial x} + \frac{\partial(\rho_l v)}{\partial y} = 0 \quad (1)$$

Momentum equations:

$$\begin{aligned} \frac{\rho_l}{\varepsilon} \frac{\partial u}{\partial \tau} + \frac{\rho_l}{\varepsilon^2} \left[\frac{\partial(uu)}{\partial x} + \frac{\partial(uv)}{\partial y} \right] = -\frac{\partial p_{eff}}{\partial x} + \frac{\mu}{\varepsilon} \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) \\ - \left(\frac{\mu}{K} + \frac{\rho_l C_D}{K^{\frac{1}{2}}} |u| \right) u + \rho_l g \alpha (T - T_m) \sin \theta \end{aligned} \quad (2)$$

$$\begin{aligned} \frac{\rho_l}{\varepsilon} \frac{\partial v}{\partial \tau} + \frac{\rho_l}{\varepsilon^2} \left[\frac{\partial(vv)}{\partial y} + \frac{\partial(uv)}{\partial x} \right] = -\frac{\partial p_{eff}}{\partial y} + \frac{\mu}{\varepsilon} \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) \\ - \left(\frac{\mu}{K} + \frac{\rho_l C_D}{K^{\frac{1}{2}}} |v| \right) v + \rho_l g \alpha (T - T_m) \cos \theta \end{aligned} \quad (3)$$

The governing intrinsic phase-averaged energy equations are written for the aluminum foams and fluid separately. Apparent heat capacity method is used to simulate heat transfer of thawing phase change growth in the aluminum foams.

Aluminum foams:

$$(1 - \varepsilon)(\rho c)_s \frac{\partial T_s}{\partial \tau} = (1 - \varepsilon)\lambda_s \left(\frac{\partial^2 T_s}{\partial x^2} + \frac{\partial^2 T_s}{\partial y^2} \right) - h(T_s - T_l) \quad (4)$$

Fluid:

$$\begin{aligned} \varepsilon(\rho c^*)_l \frac{\partial T_l}{\partial \tau} + (\rho c^*)_l [u \frac{\partial T_l}{\partial x} + v \frac{\partial T_l}{\partial y}] = \varepsilon \lambda^* \left(\frac{\partial^2 T_l}{\partial x^2} + \frac{\partial^2 T_l}{\partial y^2} \right) \\ + h(T_s - T_l) \end{aligned} \quad (5)$$

Where heat capacity and thermal conductivity of water in the pore of aluminum foams in different phase can be written as[14]:

$$c^* = \begin{cases} c_g & T < (T_m - \Delta T) \\ \frac{h_s}{2\Delta T} + \frac{c_g + c_l}{2} & (T_m - \Delta T) < T < (T_m + \Delta T) \\ c_l & T > (T_m + \Delta T) \end{cases} \quad (6)$$

$$\lambda^* = \begin{cases} \lambda_g & T < (T_m - \Delta T) \\ \lambda_g + \frac{\lambda_l - \lambda_g}{2\Delta T} [T - (T_m - \Delta T)] & (T_m - \Delta T) \leq T \leq (T_m + \Delta T) \\ \lambda_l & T > (T_m + \Delta T) \end{cases} \quad (7)$$

Initial condition:

$$T(x, y, 0) = T_{ini} \quad (8)$$

Boundary conditions:

$$-\lambda \frac{\partial T}{\partial y} = q \quad \tau > 0; y = H \quad (9)$$

$$\frac{\partial T}{\partial x} = 0 \quad \tau > 0; x = 0, x = L \quad (10)$$

$$\frac{\partial T}{\partial y} = 0 \quad \tau > 0; y = 0 \quad (11)$$

Little is known about how h varies with the conductivities and diffusivities of the phases, with the porosity and with the detailed geometry of the porous matrix. However, recent work by Shankar[9] showed that

$$Nu = \frac{hd^2}{\lambda_l} = 0.376(Re)^{0.644} Pr^{0.37} : 0.376 \left\{ (RaDa^2)^{1/2} \left(\frac{d}{H} \right) \right\}^{0.644} Pr^{-0.274} \quad (12)$$

Thermophysical properties of the ice and aluminum are presented in Table 1.

Table 1. Material properties		
Materials		
Physical properties	ice	aluminum
Thawing point (°C)	0	-----
Latent heat (kJ/kg)	334	-----
density (kg/m ³)	solid 917	
	liquid 1000	2790
Specific heat (KJ/(kg·K))	solid 2.1	
	liquid 4.2	0.881
Thermal conductivity (W/ (m·K))	solid 2.26	
	liquid 0.62	169

Numerical Solution

The governing equations have been discretized using a finite volume approach. All computations reported in this paper were carried out using a 52(X)×52 (Y) non-uniform grid after carrying out a careful grid dependence study. The time step was 0.1s. The standard SIMPLIC (Semi-implicit Method for Pressure Linked Equations Consistent) algorithm has been used to solve continuity, momentum and energy equations. A fully implicit formulation has been used for the

time-dependent terms. A line by line solver based on tri-diagonal matrix algorithm, TDMA, is used iteratively to solve the algebraic discretized equations iteratively. The initial temperature of ice and aluminum foams is 263 K

RESULTS AND DISCUSSIONS

The simulated results are presented in Figures 3-7 respectively. Fig.3 shows the variation of ice temperature with location at the mid-length of the domain for $\tau = 540s$. The porosity of the aluminum is 0.9. In Fig.3, temperature difference between top and bottom of pure ice is larger than that of ice with aluminum. The temperature distribution of ice with aluminum is more even. Because the thermal conductivity of aluminum foams is much higher than that of ice, aluminum foams filled into ice can improve its poor thermal diffusivity.

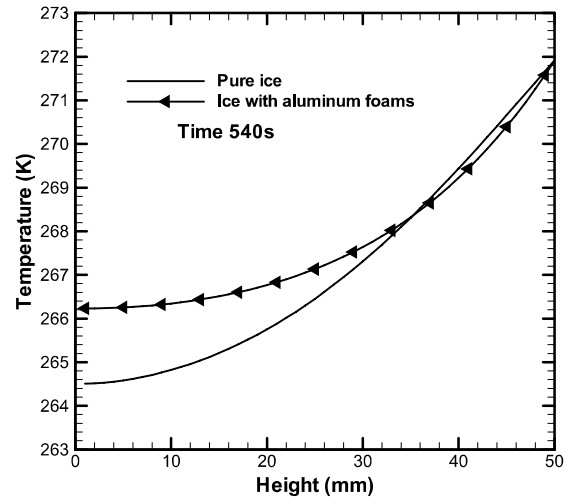


Figure 3 variation of ice temperature with location at the mid-length of the domain for $\tau = 540s$

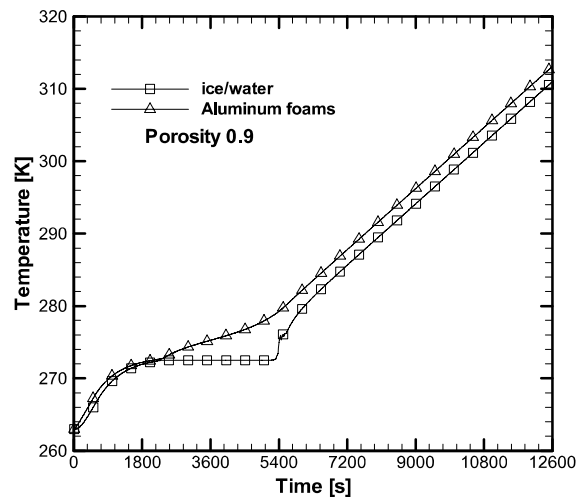


Figure 4 variation of matrix and fluid temperature with time at the bottom of the domain for $\epsilon=0.9$

Fig.4 shows the variation of matrix and fluid temperature with time at the bottom of the domain for $\epsilon=0.9$. In Fig.4, ice at the bottom of the domain undergoes three periods during

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the thawing process: solid, solid and liquid combined and liquid. During the solid period, heat transfers by conduction, while during the liquid period, heat transfer not only by thermal conduction but also by natural convection. Also, the solid response time is much faster than that of the fluid due to its higher thermal diffusivity. Solid temperature does not equal to the fluid temperature. During the solid and liquid combined period, the temperature difference between aluminum foams and fluid is larger than other period for the large latent heat of ice. Thus, a single energy equation assuming a local thermal equilibrium between the metal foams and fluid is not appropriate.

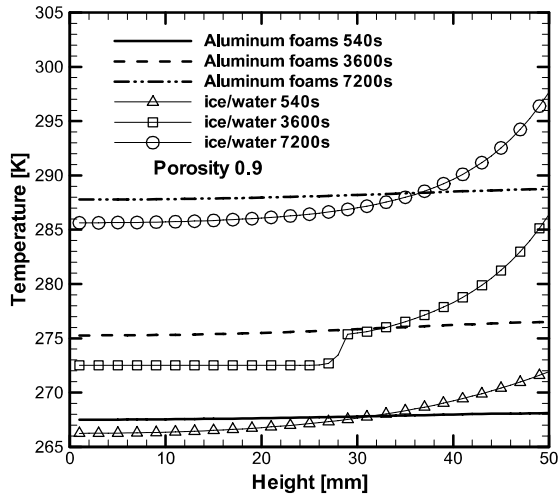


Figure 5 variation of matrix and fluid temperature with location at the mid-length of the domain ($L=25\text{mm}$) for $\epsilon=0.9$

Fig.5 shows the variation of matrix and fluid temperature with location at the mid-length of the domain ($L=25\text{mm}$) for $\epsilon=0.9$ and Fig.6 shows the variation of matrix-to-fluid temperature difference with location at the mid-length of the domain ($L=25\text{mm}$) for $\epsilon=0.9$. As is shown in Fig.5, in each period of the thawing, the temperature distribution of aluminum foams is almost uniform due to its high thermal diffusivity. Temperature of aluminum foams is higher than that of fluid at the top of the domain and that is opposite at the bottom of the domain, so at the top of the domain heat transfers from fluid to aluminum foams, while at the bottom of the domain heat transfers from aluminum foams to fluid. The temperature difference between aluminum foams and fluid is shown in Fig.6. The matrix-to-fluid temperature difference is high at 540s, and this is the phase change period. The matrix-to-fluid temperature difference at 9000s is the same as that at 7200s, so we can indicate that during the phase change period the matrix-to-fluid temperature difference is higher than other period, and after 7200s aluminum foams and fluid reaches quasi-steady-state which is also shown in Fig.4.

Fig.7 shows that decreasing porosity can play a good role on enhancing the thawing process. However, this will reduce the fluid motion and also will be at the expense of the quantity of PCM and, consequently, the storage capacity of the PCM storage.

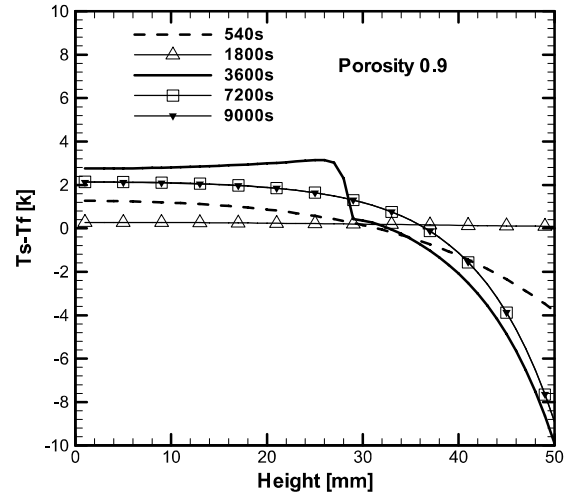


Figure 6 variation of matrix-to-fluid temperature difference with location at the mid-length of the domain ($L=25\text{mm}$) for $\epsilon=0.9$

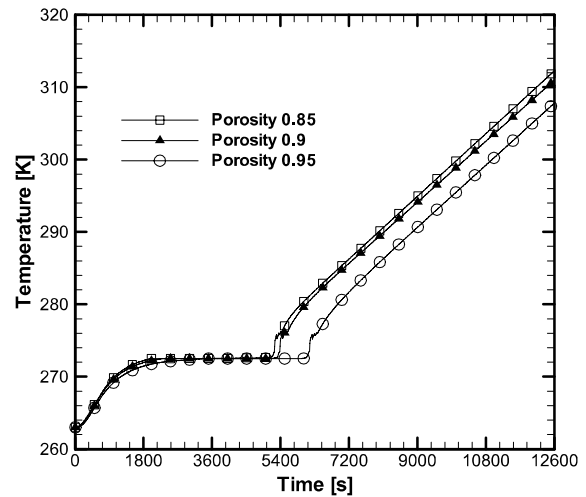


Figure 7 variation of fluid temperature with time at the bottom of the domain

CONCLUSIONS

The thawing heat transfer process of ice filled with aluminum foams is studied. By comparing the thawing process of ice with and without the porous aluminum foams, it is found that the presence of the aluminum foams has a great effect on the heat transfer and thawing rate of the PCM energy storage. During the thawing process, there is temperature difference between matrix and fluid. A single energy equation assuming a local thermal equilibrium between the metal foams and fluid is not suitable and a two temperature model is necessary. Decreasing the porosity of the aluminum foams increases the thawing rate. The aluminum foams acts to substantially decrease the response time of the system and may, thus, lead to far less overheating during the transient.

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