

Study on Improvement of Thermal Conductivity for Pcms Using a Verse Problem Method

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Abstract: Based on the model of phase change heat conduction, an inverse problem method which combines experiment with numerical calculation is developed to study the improvement of thermal conductivity when metal promoters are added. The results show that the higher the thermal conductivity of the promoter, the higher the effective thermal conductivity of PCMs(Phase Change Materials). When same ratio of promoter is added, greater improvement will be obtained for low thermal conductivity PCMs than high ones.

Keywords: PCMs, phase change, inverse problem, effective heat conductivity

NOMENCLATURE

T temperature (°C)
 a thermal diffusivity (m²/s)
 Ste Stefan number, $c(T_w - T_m)/L$
 r integer larger than 2

Subscripts

l liquid
 s solid
 m freezing point

ρ density (kg/m³)
 c specific heat (kJ/kg · K)
 L latent heat (kJ/kg)
 k thermal conductivity (W/m · K)

i initial
 h added promoter
 p phase change material

1. INTRODUCTION

Phase change materials (PCMs) are prime candidates for use as thermal energy storage media because of their superior energy storage capacities. They should possess a high density, high specific heat, high thermal conductivity, congruent melting, small volume change, little supercooling and so on. However, it is practically difficult to find or develop PCMs that satisfy all desirable qualities. In many cases, unsuitable properties are improved using some techniques. For instance, thermal conductivity promoters such as aluminum, copper and wire netting are frequently used for the PCMs with low thermal conductivities. It is important to know the relationship between the effective thermal conductivity of mixed PCMs and the ratio of the promoters. The paper develops a new method which combines experiment with numerical calculation to determine the effective thermal conductivity of PCMs when thermal conductivity promoters are added.

2. MATHEMATICAL MODEL

For the phase change problem in limited area, the Neumann model can predict the process of phase

change well at initial time. If the natural convection in the liquid area could be neglected, the mathematical model is as follows.

Solid area,

$$\frac{\partial^2 T_s}{\partial x^2} = \frac{1}{a_s} \frac{\partial T_s}{\partial t} \quad x=0, T_s = T_w \quad (1)$$

Liquid area,

$$\frac{\partial^2 T_l}{\partial x^2} = \frac{1}{a_l} \frac{\partial T_l}{\partial t} \quad (2)$$

$$x=b, \frac{\partial T_l}{\partial x} = 0; \quad t=0, T_l = T_i$$

At interface,

$$k_s \frac{\partial T_s}{\partial x} - k_l \frac{\partial T_l}{\partial x} = \rho L \frac{\partial S}{\partial t} \quad (3)$$

$$x = S(t), T_s = T_l = T_m$$

According to the analysis method^[1], the interface of

solidification can be determined according to (4).

$$S = 2K(a_s t)^{1/2} \quad (4)$$

where

$$\frac{Ste}{K\sqrt{\pi}} \left[\frac{e^{-K^2}}{\text{erf}(K)} + \frac{k_l}{k_s} \left(\frac{\alpha_s}{\alpha_l} \right)^{1/2} \cdot \frac{T_m - T_i}{T_m - T_w} \cdot \frac{1}{Z_n} \right] = 1 \quad (5)$$

$$Z_n = \frac{r+1}{r\sqrt{\pi}} (-v + \sqrt{v^2 + \frac{2r}{r+1}}),$$

$$v = K \left(\frac{\alpha_s}{\alpha_l} \right)^{1/2}$$

$$Ste = \frac{c_s (T_m - T_w)}{L}$$

If the initial temperature was at its freezing point $T_i = T_m$, then (5) can be simplified as

$$\sqrt{\pi} K \exp(K^2) \text{erf}(K) = Ste \quad (6)$$

Based on (4)

$$a = \frac{S(t)^2}{4K^2 t}, \quad k = \frac{\rho c S(t)^2}{4K^2 t}$$

The effective thermal conductivity k_{eff} can be defined as

$$k_{eff} = \frac{\rho_{eff} c_{eff} S(t)^2}{4K^2 t} \quad (7)$$

where, ε presents the quality ratio of the thermal conductivity promoters.

$$\rho_{eff} = \rho_h \varepsilon + \rho_p (1 - \varepsilon) \quad (8)$$

$$c_{eff} = [c_h \varepsilon \rho_h + c_p (1 - \varepsilon) \rho_p] / \rho_{eff} \quad (9)$$

$$L_{eff} = \rho_p L (1 - \varepsilon) / \rho_{eff} \quad (10)$$

If the interface is obtained, the effective thermal conductivity k_{eff} can be calculated.

The photographic experiment was employed to track the practical interface and the experimental apparatus are as Figure 1. The cooling water for experiment was produced by the refrigerator unit and stored in the water tank. its temperature was controlled by the temperature controller. The initial temperature of PCM in the test cell was kept uniform and maintained at a temperature slightly above the freezing point by circulating a constant temperature water in heat exchanger of the cell. The test cell is made up of an enclosure of a rectangular cross section with inside dimensions of 50mm in width, 280mm in height and 400mm in depth. The front and back side of the cell were made of plexiglass to enable the interface to be visualized. When solidification was initiated, the cooling

water is pumped to the heat exchanger of the experimental cell and one side of the cell can be kept at a constant lower temperature than the freezing point of the PCM. Then the PCM in the cell will be solidified gradually and the interface will be recorded by digital camera at selected time intervals.

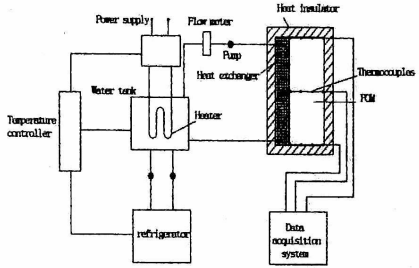


Figure 1: Schematic diagram of the experimental apparatus

Considering the effect of natural convection on the shape of interface (Figure.2), the average interface location is given by

$$S_{ave} = \frac{\int_0^H X dy}{H} \quad (11)$$

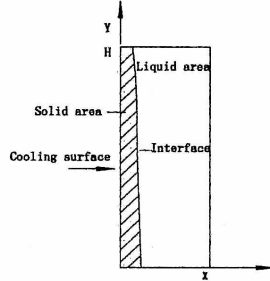


Figure 2: Sketch map of interface in solidification experiment

According to (7) and (11), the effective thermal conductivity can be obtained. To lower the measurement error in inverse problem, the assumed thermal conductivity will be employed to solve the interface-time relationship by right problem method through numerical calculation. Then the calculation results will be compared with that of the experiment and the corresponding thermal conductivity of the most close curve to the experimental value is the effective thermal conductivity.

3. SOLUTION PROCEDURES

The effective thermal conductivity of PCMs will increase when thermal conductivity promoters are added and agree with the relations $k_p < k_{eff} < k_h$.

During right problem solution, proper increment will be determined by

$$\Delta k = (k_h - k_p) / m \quad (12)$$

From $k = k_p$ to $k = k_h$, every thermal conductivity value will be substituted into (4) and the corresponding interface locations $S_m(t)$ will be obtained when the temperature of the cell wall T_w is given. Similarly, the average interface location S_{ave} under the same condition will be obtained by experiment. To reduce the effect of error, for every thermal conductivity value, the numerical calculation will be performed n times at different time. The corresponding experimental interface locations will be recorded at the same time calculation selected.

For every assumed thermal conductivity, the numerical calculation results will be compared with the experimental value and the sum of variance will be calculated by

$$G = \sum_{i=1}^n (S_m - S_{ave})^2 \quad (13)$$

The smaller the G value, the smaller the discrepancy between the calculation and the experiment interface value. The corresponding assumed thermal conductivity of the smallest G value is the effective thermal conductivity. Based on the method, the effective thermal conductivity can be estimated when different ration and type of promoters are added. Thus, the effect of ratio and the material of promoters on the thermal conductivity of PCM will be investigated.

4. CALCULATION CASE

In this work, water, Octadecane and Monoethanolamine were used as PCMs and the aluminum powder and wire netting were used as promoters. The thermophysical properties of PCM and the promoter are showed as Table.1 and Table.2.

Table 1: Thermophysical properties of PCMs

PCMs	T_m (°C)	k [W/(m · K)]	ρ (kg/m ³)	c [kJ/(kg · K)]	L (kJ/kg)
H ₂ O	0	0.60	1000	4.19	333
		2.26		2.00	
Monoethanolamine	10.2	0.19	1016	3.36	184
		0.81		2.01	
Octadecane	28	0.15	850	2.20	243
		0.42		1.80	

Table 2: Thermophysical properties of promoters

Promoter	ρ (kg/m ³)	c [kJ/(kg · K)]	k [W/(m · K)]
aluminum powder	2690	0.905	237
wire netting	7850	0.465	43

Table 3: Increment of thermal conductivity

Name of PCMs	6% wire netting	12% wire netting	6% aluminum powder	12% aluminum powder
H ₂ O	5.5%	11.2%	13.5%	16.4%
Monoethanolamine	8.6%	14.1%	16.3%	25.7%
Octadecane	10.3%	17.3%	18.6%	36.1%

According to the inverse method, the effective thermal conductivity of above 3 PCMs will be obtained when the promoter are added.

The different increment of thermal conductivity

corresponding to different promoter are showed in Table.3. The errors are within 15% compared with the literatures [2,3].

From Table.3 it can be see that, when same ratio

of metal is added, greater improvement will be obtained for low conductivity PCMs than for high conductivity PCMs. The greater the thermal conductivity of the promoter, the greater the effective thermal conductivity of the PCMs.

5. CONCLUSIONS

5.1 An inverse problem method which combines experiment with numerical calculation is developed to study the improvement of thermal conductivity when metal is added. The results agree well with relevant literatures and the method is effective to study the improvement of thermal conductivity under phase change condition.

5.2 The results also show that the higher the thermal conductivity of the promoter, the higher the effective thermal conductivity of PCMs. When same ratio of metal is added, greater improvement will be obtained for low conductivity PCMs than for high conductivity

PCMs. The proper promoters are important for low thermal conductivity PCMs to improve their energy storage performance.

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