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Enhanced Freezing in a Finned Enclosure Filled with Nanofluid

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***Abstract*— This study numerically investigated the freezing behavior of nanofluid in a rectangular enclosure with installed fins. A suspension of copper nanoparticles in water was used as a nanofluid. According to numerical experiment results, we examined the effects of the number of fins and the fraction of nanoparticles on freezing. Results suggest that freezing is more enhanced by nanofluid than by fins at the same filling volume fraction.**

***Index Terms*— Freezing, Fin, Nanofluid, Numerical solution.**

I. INTRODUCTION

Smooth phase change is important for latent heat storage devices. However, a general phase change material (PCM) with large latent heat has the important shortcoming of low thermal conductivity. Additionally, a difficulty exists by which ice formed on a freezing front acts as thermal resistance to hinder phase change. Recent studies have specifically examined enhanced phase change in a latent heat storage device with metal nanoparticles added to PCM to compensate these shortcomings [1], [2].

Research to encourage phase change by expanding the heat transfer area using fins has been conducted for many years [3], [4]. Nevertheless, few studies have examined the promotion of phase change using both fins and nanofluid simultaneously, and no conclusion seems to have been reached on what effects of an enlarged heat transfer area by fins and enhanced thermal conductivity by nanofluid are dominant. Therefore, to ascertain which of nanofluid or fins is more effective in encouraging phase change, we numerically investigated the phase change problem in a case where the nanofluid is filled as a PCM in a rectangular enclosure with installed fins.

II. NUMERICAL PROCEDURE

A. Physical Model

Figure 1 presents a numerical analysis model and a two-dimensional orthogonal coordinate system adopted for this study. The calculation region has width W = 100 mm, height H = 100 mm, and aluminum fins of L_{XB} = 5 mm, L_{YT} = 4 mm, and L_{XF} = 20 mm arranged at regular intervals. The enclosure is filled with water as a PCM with copper nanoparticles added.

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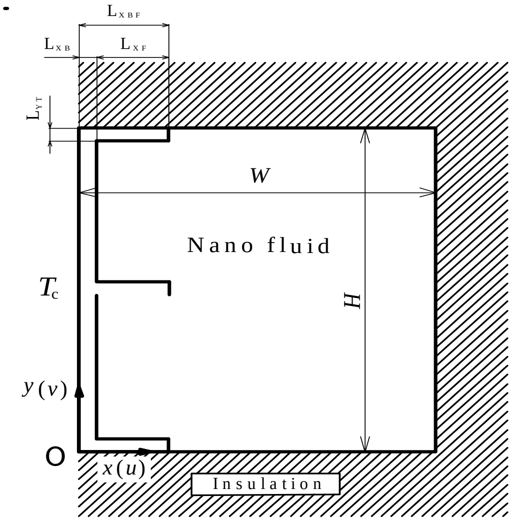


Fig. 1 Schematic drawing of the physical model and coordinate system

The filling volume fraction of nanoparticles φ was set to 0, 0.016, and 0.032, whereas a fin occupies 0.008 of the volume of the enclosure. In short, inserting one fin into the system is equivalent to adding copper nanoparticles of a volume fraction of 0.008 in terms of decreased PCM.

B. Governing Equations

For the numerical analysis presented herein, incompressible and laminar flow and Boussinesq approximation are assumed. Volume change is not considered in the phase change. Under these assumptions, the governing equations [1] are the following.

/Continuity/

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

/Momentum (x-direction)/

$$\rho_{\mathrm{nf}}\frac{\partial u}{\partial t}+\rho_{\mathrm{nf}}u\frac{\partial u}{\partial x}+\rho_{\mathrm{nf}}v\frac{\partial u}{\partial y}= -\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}\left(\mu_{\mathrm{nf}}\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_{\mathrm{nf}}\frac{\partial u}{\partial y}\right) \tag{2}$$

/Momentum (y-direction)/

$$\rho_{\mathrm{nf}}\frac{\partial v}{\partial t}+\rho_{\mathrm{nf}}u\frac{\partial v}{\partial x}+\rho_{\mathrm{nf}}v\frac{\partial v}{\partial y}= -\frac{\partial p}{\partial y}+\frac{\partial}{\partial y}\left(\mu_{\mathrm{nf}}\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_{\mathrm{nf}}\frac{\partial v}{\partial y}\right)+\rho f_{\mathrm{L}}g\beta(T) \tag{3}$$

/Energy (PCM)/

$$\rho_e c_e \frac{\partial T}{\partial t} + \rho_{nf} c_{nfL} u \frac{\partial T}{\partial x} + \rho_{nf} c_{nfL} v \frac{\partial T}{\partial y} = \frac{\partial}{\partial x}\left(\lambda_e \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_e \frac{\partial T}{\partial y}\right) - \rho_{nf} L_{nf} \frac{\partial f_L}{\partial t} \qquad (4)$$

/Energy (Fin)/

$$\rho_{Al} c_{Al} \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda_{Al} \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_{Al} \frac{\partial T}{\partial y}\right) \qquad (5)$$

Therein, *u* and *v* respectively represent velocity components in the *x* and *y* directions. Also, ρ and μ respectively denote density and the viscosity coefficient. *t* stands for time. *p* denotes pressure. *g* is gravitational acceleration. β(*T*) is the coefficient of thermal expansion considering the water density inversion. f_L represents the liquid volumetric fraction. *T* stands for temperature. *c* denotes specific heat. λ expresses thermal conductivity. *L* signifies latent heat. Subscripts "nf", "e", and "Al" respectively denote nanofluid, mixed nanofluid consisting of a solid phase and a liquid phase (phase change region), and aluminum.

The initial temperature of the nanofluid is 4 °C. The left wall temperature (T_c) is fixed at -5 °C. The other walls are insulated.

C. Liquid fraction and Physical properties

In this numerical analysis, three phases might exist in the nanofluid of the system: a solid phase, phase change region, and a liquid phase. Letting the volume fraction of the solid phase be f_S with respect to the volume fraction f_L of the liquid phase, the following relational expression is obtained.

$$f_L + f_S = 1$$

(6)

In that equation, f_L varies depending on the temperature as described by Kashini et al. [1]. It is defined as

$$f_L = \begin{cases} 0 & (T \le -DTF) \\ \dfrac{T + DTF}{T_{ph} + DTF} & (-DTF < T < T_{ph}) \\ 1 & (T_{ph} \le T) \end{cases}$$

(7)

Where T_{ph} stands for the freezing point. Also, 0 °C and *DTF* is generally 0.1 ° C as adopted in this study.

Various physical property values in the phase change region are derived from corresponding values in the solid and liquid phases as shown below.

/Density/

$$\rho_e = f_L \rho_{nfL} + (1 - f_L)\rho_{nfS}$$
$$\rho_{nfL} = (1-\varphi)\rho_L + \varphi\rho_{Cu} \qquad (8)$$
$$\rho_{nfS} = (1-\varphi)\rho_S + \varphi\rho_{Cu}$$

In those equations, subscripts "nfL" and "nfS" respectively represent the liquid phase and solid phase of the nanofluid. Subscript "Cu" denotes copper. For simplicity, assuming $\rho_S = \rho_L$, then $\rho_{nfL} = \rho_{nfS}$. By rewriting them as ρ_{nf}, Eq. (8) becomes the following.

$$\rho_e = f_L \rho_{nf} + (1 - f_L)\rho_{nf}$$

(9)

/Specific heat/

$$c_e = f_L c_{nfL} + (1 - f_L) c_{nfS}$$
$$c_{nfL} = (1-\varphi)c_L + \varphi c_{Cu}$$
$$c_{nfS} = (1-\varphi)c_S + \varphi c_{Cu}$$

(10)

/Thermal conductivity/

$$\lambda_e = \frac{(\lambda_{nfL} + \lambda_d)\lambda_{nfS}}{(1 - f_L)(\lambda_{nfL} + \lambda_d) + f_L \lambda_{nfS}}$$
$$\lambda_{nfL} = (1-\varphi)\lambda_L + \varphi\lambda_{Cu}$$
$$\lambda_{nfS} = (1-\varphi)\lambda_S + \varphi\lambda_{Cu}$$

(11)

In those equations, λ_d is calculated using a formula presented by Wakao et al. [5].

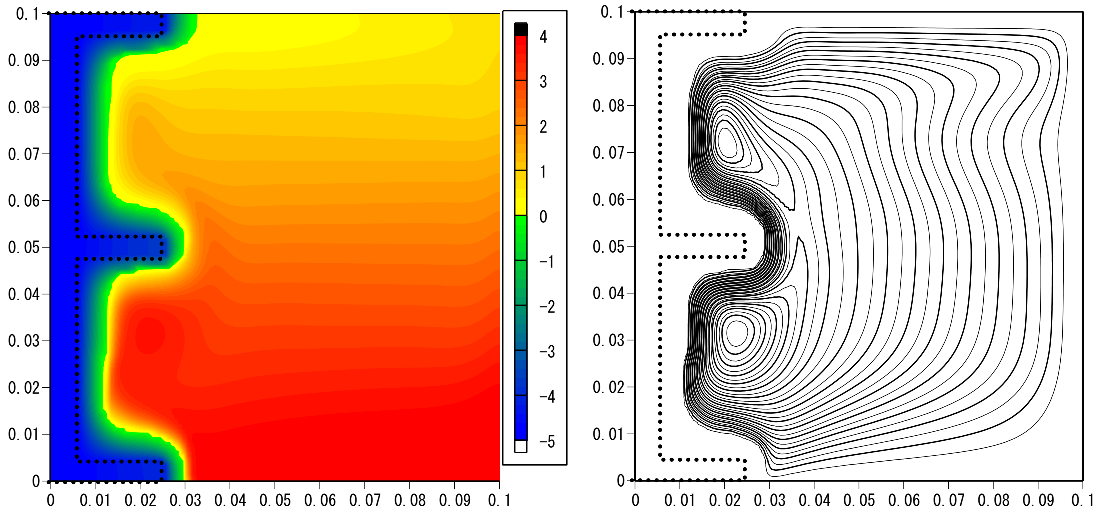
III. RESULTS AND DISCUSSION

Figure 2 portrays (a) the isotherms and (b) streamlines at a freezing time of 600 s of a pure PCM without nanoparticles (water, φ = 0). It is noteworthy that water at 0 °C near the freezing front is less dense than that at 4 °C because of density inversion. The streamlines near the freezing front are dense. A strong upward flow is generated by buoyancy because of a large temperature variation in this region. In addition, two convective cells are observed at a part slightly distant from the freezing front because a low-temperature fluid ascending near the freezing front is warmed by the surrounding fluid, detached from the freezing front, and turned downward. These descending flows mutually merge at locations away from the fins to form a large clockwise cell. The temperature distribution also suggests that low-temperature fluid is stagnant at the top of the enclosure. Most of the lower part is nearly at the initial temperature (4 °C) in this instance. The isotherms are disturbed near the fins, but they are mostly layered at the top of the enclosure. A freezing front can be observed progressing along the profile of the fins. Detailed observation of the middle fin reveals enhanced freezing on the upper surface compared to the lower surface. Freezing is hindered probably because the upward flow collides with the lower surface. Similar interpretation applies on the top surface of the bottom fin and the lower surface of the top fin. In the same conditions as those depicted in Fig. 2, calculation results with more time elapsed are shown in Fig. 3, in which (a) and (b) respectively denote the isotherms and streamlines at a freezing time of 10,800 s. The left half of the enclosure is almost frozen. The two convection cells near the fins have disappeared. The large clockwise convective cell that is present in the right half has also weakened remarkably. Moreover, the freezing front is slightly wavy depending on the fin profile, but it is almost parallel to the cooling surface. This phenomenon is thought that to have occurred because ice formed near the fins acts as thermal resistance.

Results of freezing calculation for a nanofluid of copper nanoparticles suspended in water are shown in Fig. 4, in which (a) and (b) respectively show the isotherm and streamlines at a volumetric filling fraction φ of 0.032 and a liquid phase is observable. Fig. 5 presents calculation results obtained after a lapse of a freezing time of 10,800 s, in which (a) and (b) respectively show the isotherms and the streamlines. Only about 20% of the liquid phase is left in the system. In addition, a large region of the solid phase has

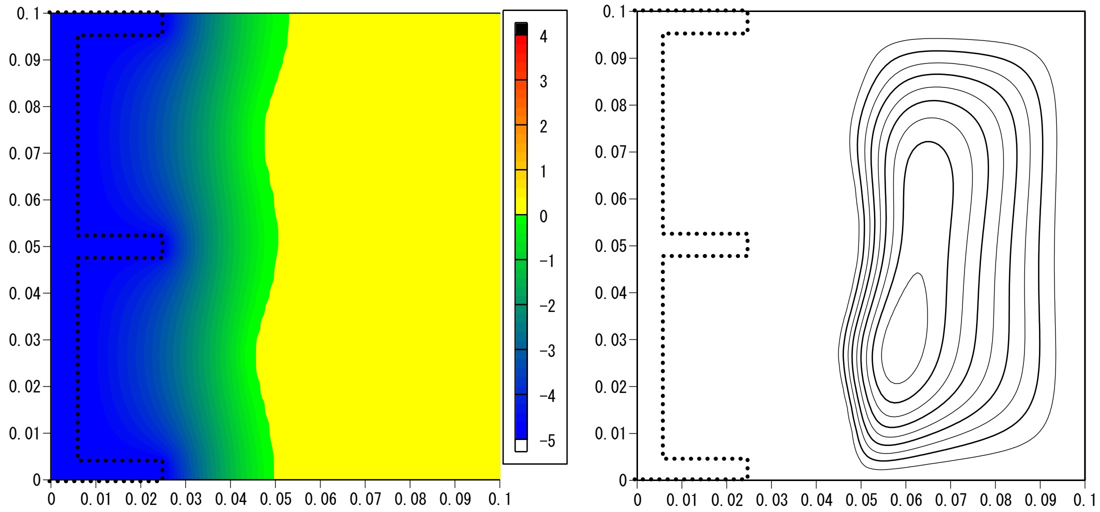
freezing time of 600 s. Comparison with Fig. 2 indicates a remarkably progressed freezing front. Its shape is similarly wavy over all fins. Most of the unfrozen region has a temperature of 1 °C or lower, which indicates that the temperature is decreasing considerably. The two convection cells, observed likewise in the case without nanoparticles (Fig. 2), have already disappeared. One convective cell in the entire

reached the boundary temperature of the left wall, -5 °C. Thermal conduction dominates heat transfer in the system. Therefore, the results show that freezing can be encouraged remarkably simply by adding only copper nanoparticles of a volume fraction of 0.032 to a pure PCM as the base.



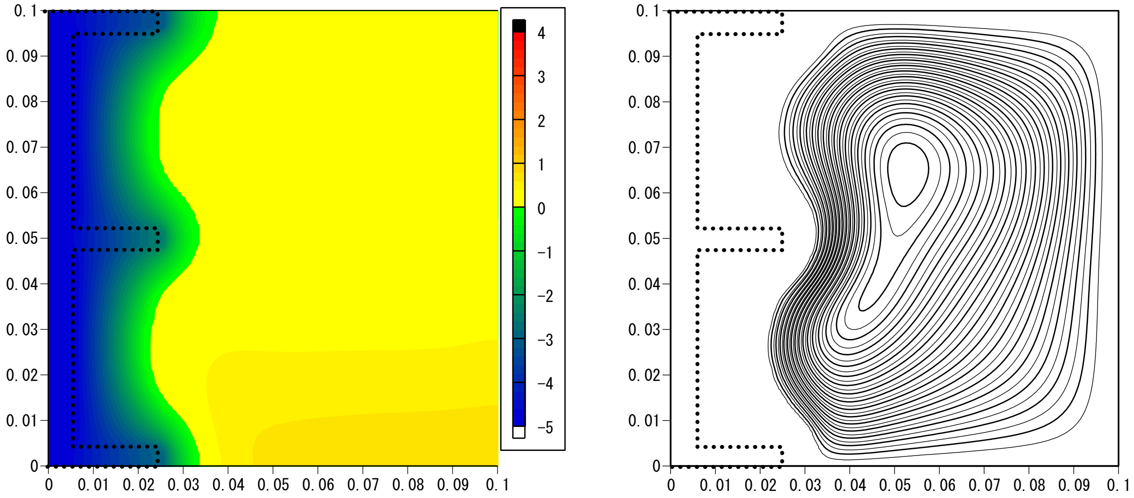
(a) Isotherms [°C] **(b) Streamline**

Fig. 2 Numerical analysis results without nanoparticles (*φ* = 0) at 600 s



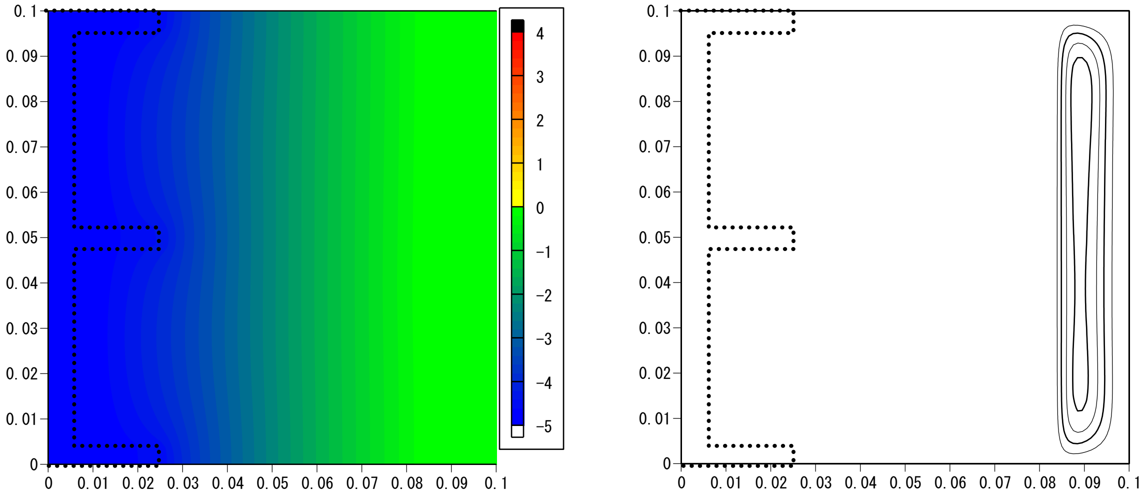
(a) Isotherms [°C] **(b) Streamline**

Fig. 3 Numerical analysis results without nanoparticles (*φ* = 0) at 10,800 s



(a) Isotherms [°C] **(b) Streamline**

Fig. 4 Numerical analysis results with nanoparticles (φ = 0.032) at 600 s



(a) Isotherms [°C] **(b) Streamline**

Fig. 5 Numerical analysis results with nanoparticles (φ = 0.032) at 10,800 s

Finally, the time variation of freezing volume fraction is shown in Fig. 6. The numbers of fins are 0, 2, 3, and 4. The filling fraction of copper nanoparticles is 0, 0.016, and 0.032. It is noteworthy that, even when the number of fins is 0, an aluminum base component with thickness of 5 mm is installed in the enclosure.

First, we compare the effects of "an enlarged heat transfer area by fins" to "enhanced thermal conductivity by nanofluid." It takes about 31 h for the system to reach complete freezing without adding nanoparticles and with no fin inserted (φ = 0, 0-fin). The necessary time is only about 23 h without nanoparticles with two fins inserted (φ = 0, 2-fin). In short, the time to complete freezing can be shortened to about 75% with a two-fin configuration. The amount of PCM decreased by insertion of two fins is equivalent to 0.016 of a filling fraction of copper nanoparticles. In other words, a φ = 0.016, 0-fin system and a φ = 0, two-fin system are comparable by identical criteria. The time of about 8 h necessary to complete freezing at φ = 0.016 with no fin (φ = 0.016, 0-fin) can be reduced to about 26% compared with the case of φ = 0, 0-fin. From those results, it can be concluded that adding nanoparticles is more effective for freezing enhancement than inserting fins into a system.

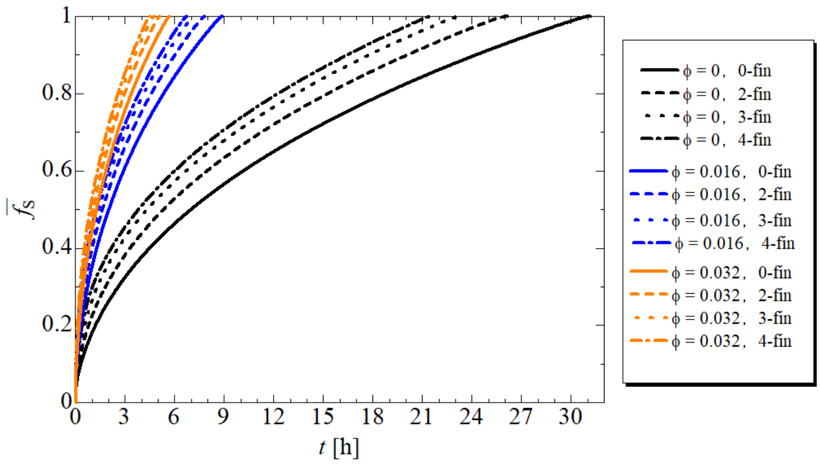


Fig. 6 Time variation of the freezing volume fraction

Next, the time required for the entire system to be frozen is compared at 0-fin configurations. Complete freezing at $\varphi = 0$ takes about 31 h for 0-fin as described above, but the time can be shortened to about 9 h at $\varphi = 0.016$. However, even if the filling amount is doubled (i.e. $\varphi = 0.032$), the time to complete freezing is shortened only to about 6 h. In other words, considering decrease in PCM amount by substitution, one can conclude that an optimum value exists for the volume fraction of copper nanoparticles in a PCM. Our future subject is to ascertain this optimum value.

The decrease in the freezing rate is small even after 3 h (10,800 s) of freezing time in the case of $\varphi = 0.032$. As shown in Fig. 5, heat conduction has become dominant in the freezing system by a freezing time of 3 h. In other words, improved heat conduction in solid phase nanofluid encourages freezing greatly with addition of nanoparticles, rather than enhanced heat transfer by convection.

IV. CONCLUSION

To ascertain which of nanofluid or fins is more effective in encouraging phase change, we numerically investigated the freezing phenomena of the nanofluid in an insulated rectangular enclosure with installed fins. Especially, we focused the effects of number of fins and the fraction of nanoparticles on freezing.

As a result, it takes about 31 h for the system to reach complete freezing without adding nanoparticles and with no fin inserted ($\varphi = 0$, 0-fin). The necessary time is only about 23 h without nanoparticles with two fins inserted ($\varphi = 0$, 2-fin). In short, the time to complete freezing can be shortened to about 75% with a two-fin configuration. The time of about 8 h necessary to complete freezing at $\varphi = 0.016$ with no fin ($\varphi = 0.016$, 0-fin) can be reduced to about 26% compared with the case of $\varphi = 0$, 0-fin. Therefore, it can be concluded that adding nanoparticles is more effective for freezing enhancement than inserting fins into a system.

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