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Melting of Ice on the Heating Plate with Split Fins

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Key words: PCM, Melting, Latent heat, Thermal storage, Split fin

Abstract

One of the important applications of a contact melting process is a latent thermal energy storage system owing to its high heat flux and small temperature variation. In some previous works, the split fins have been employed in order to enhance the melting rate. In the present work, the direct contact melting was experimentally investigated using an ice as specimen for both split and non-split fins. It was shown that the contact melting by split fins increases the melting rate compared to that of non-split ones.

Nomenclature

A : cross sectional area [m^2]
h : heat transfer coefficient [W/m^2]
k : thermal conductivity [W/(m · k)]
L : length [m]
M : mass
P : perimeter [m]
q : heat flux
T : temperature [℃]
t : time [sec]

Subscripts

0 : surrounding fluid
m : melting point
T : initial state
t : fin-tip
w : fin base

1. Introduction

In direct contact melting, a very thin liquid-filled film exists between solid PCM (phase change material) and a heating plate. The liquid yielded by melting is continuously flowed *out from the film by force which pressed the* solid against the plate. Heat flux across a thin film from the heating surface to the solid is much higher than that of heat transfer dominated by *natural convection. This phenomenon* was studied sufficiently by analyses and experiments$^{(1-9)}$ including researches to enhance the heat transfer coefficient,$^{(10-12)}$ and its characteristics *induced many researchers to apply* actively to the thermal storage system.

While several methods of thermal energy storage were developed in the past years, *utilization of latent heat has been spotlighted*

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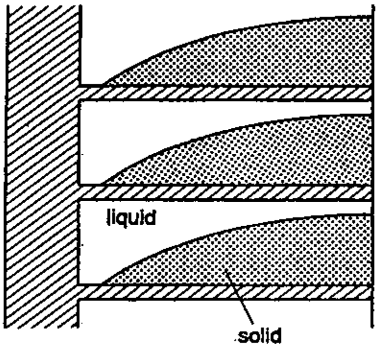


Fig. 1 Thermal storage system with inner horizontal plate fins.

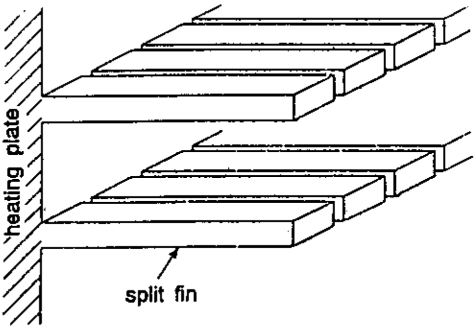


Fig. 2 Sketch of a heating plate with split fins.

in the field of practical system. The latent heat thermal energy storage has properties of a large amount of energy per volume accumulated in a storage tank and a small temperature variation during melting and freezing processes. This permitted many researchers to study behaviors in solid-liquid phase change process.

Saito et al.(13) compared several types of storage tank proposed at that time and concluded that the type utilizing direct contact melting is much superior to that by natural convection with respect to the melting rate. Also, a heat transfer plate with horizontal plate fins was developed by Nagakubo and Saito(14) shown in Fig. 1, where the direct contact melting occurs between the solid and fin surfaces. It turned out that the melting rate increases notably since direct contact melting takes place on a large number of fins. Saito et al.(10) have reported another efficient method to promote the melting rate, that is, a split heating plate with slots to decrease the average melt travel distance while the total area of the heating plate remains. It proved that an increasing effect of heat flux was accomplished and that the increasing rate becomes greater as the number of split becomes larger. Saito and Hong(15) applied the split heating plate (Fig. 2) to the latent heat thermal energy storage system, having both the fin and the split-heating-plate effect and showed that the melting rate is apparently increased using octadecane as specimen.

In these studies for an encapsulated chamber, paraffin and octadecane were almost used as a specimen, but in actual systems an ice is used as the material of latent heat storage material. The reason is that for the ice, there are some difficulties related to volumetric expansion and formation of transparent ice without voids. In the present study, we used the ice as specimen to verify whether the heating plate with split fins is effective in ice thermal storage system as well.

2. Experiment

The main components of the experimental device shown in Fig. 3 are two main bodies, three constant temperature baths, data acquisition system, video cameras and brine piping. The two main bodies have the same appearance and condition except fins: the one with split fins and the other with non-split fins for direct comparison of fin-split effect. The main body (Fig. 4) of experimental device consists of the heating plate made of copper and 9 injection tubes through which the brine impinges the back surface of the heating plate. By this method, the heating plate has a uniform temperature distribution on its surface. To visually observe and take a picture of the melting pro-

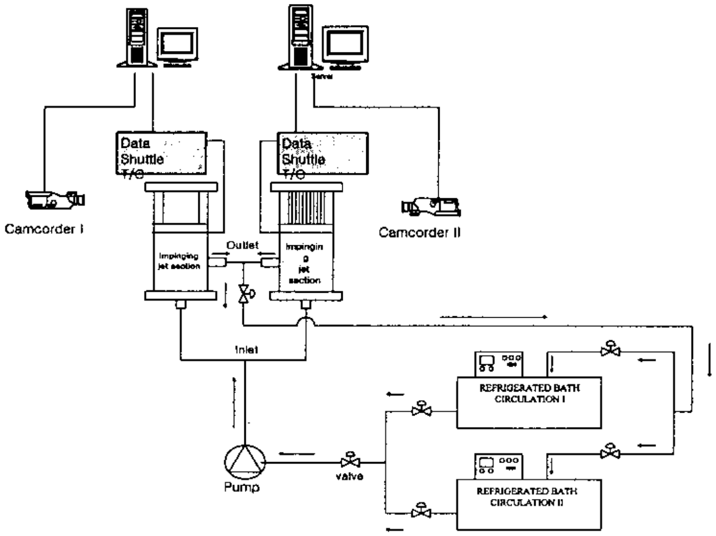


Fig. 3 Schematic of experimental apparatus.

cess, the frame of the main bodies was made of acryl 20 mm in thickness. The chamber of phase change material is divided into four equal spaces (height 11 mm, width 44 mm, depth 53 mm) by five fins.

For the main body with split fins, each fin made of copper plate with 2 mm in thickness is split in parallel to the direction that heat primarily transfers from heating plate. The pitch and gap of slot are 4.4 mm and 1 mm, respectively. The surface of fin is polished using very fine sandpaper so that the direct contact melting takes place on mirror face. To minimize the contact resistance between the heating plate and the fins, the heating plate is grooved in a depth of 4mm and the fins are tightly inserted into these grooves and solder-fixed. The main body with non-split is made under the same condition except fins.

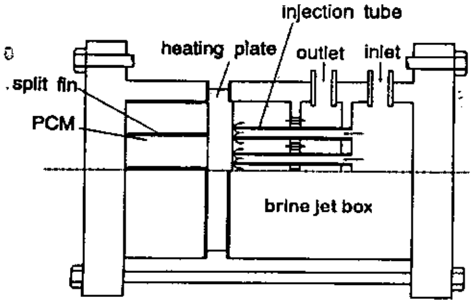


Fig. 4 Main body of experimental apparatus.

To maintain two main bodies under experimentally identical conditions, the circulation piping of brine is equipped symmetrically. Three constant temperature brine baths were prepared for adjusting the temperature of the ice and the heating plate. The one for freezing and preheating the ice at the temperature slightly lower than the melting point; the other baths served as the thermal environment for the heating plate during experiment.

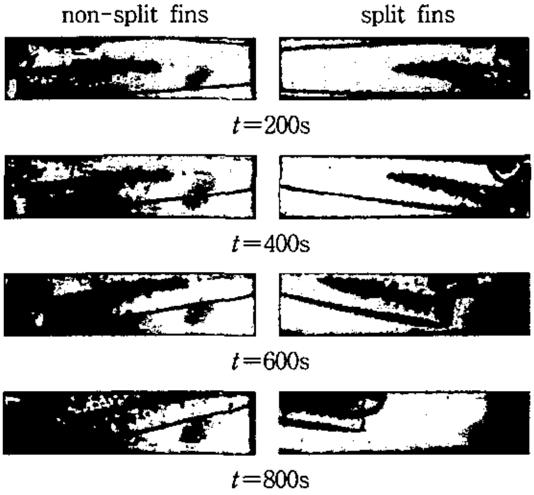
Thermocouples are installed to measure the temperatures, which are located at the heating plate, the tip of fin and the inlet and exit of brine tube. The thermocouples are inserted at four points inside the heating plate 25 mm in depth, but the temperature differences are very small in actual experiments so the measured temperatures are averaged as that of the heating plate. The temperatures are acquired by two data loggers and saved at a personal computer.

As the test material, the ice was chosen since it is used popularly in latent thermal energy storage system. However, it is very difficult to prepare transparent ice including no void. First of all, the water should be frozen as slowly as possible to minimize a thermal stress in ice. The air mixed in water and the vapor generated in freezing can be included in the ice and prevent the direct contact melting if these exist in the gap between the ice and heating surface. Hence, we continuously injected fresh air from outside onto the solid-liquid interface, which gets rid of the vapor near the interface and makes successfully the ice transparent. In the experiment, the ice was formed by circulating the brine at −5℃ for two hours in a state that the fins of the main bodies are positioned vertically. In this process, volumetric expansion of ice requires the removal of water additionally.

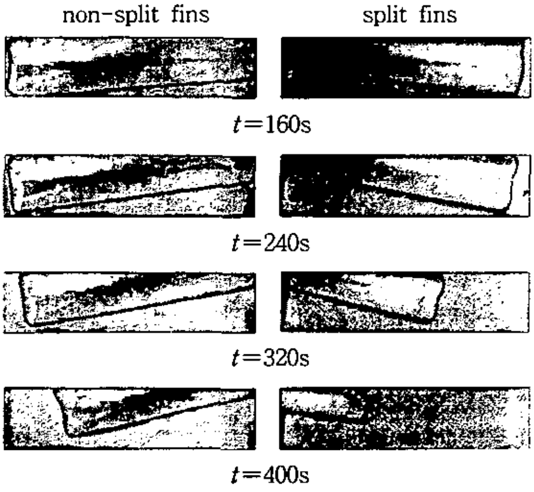
In a melting process, the main body was inclined at 4° from horizon to contact the ice to both the heating plate and fins. The inclination gives no effects on melting rate from the reference [15]. After freezing water, the ice was initiated at melting point by circulating the brine at 1.5℃ during two hours. Before melting, for the ice to move freely in the chamber, all acryl side-walls were heated by lamps of 400 W during 40~60 sec, which led to thin liquid gaps between the acryl wall and the ice. By this means, these liquid gaps have a role of passage of molten liquid. Though lots of factors can influence the melting rate and pattern, the temperature of heating plate was taken as a parameter. It will be discussed later; the length of fin has a significant effect on melting pattern, too.

3. Results and discussion

The patterns of melting were identified by observation of the shape of the solid-liquid interface using video camera. Representative photographs are shown in Fig. 5 (a) for $\Delta T_w=7$℃ and Fig. 5 (b) for $\Delta T_w=20$℃, where ΔT_w refers to the difference between the temperature of heating plate T_w and the melting point T_m. In these figures, the left-hand side is for non-split and the right-hand side for split fins, and the heating plate is located at the center of two figures to easily compare the melting rate. Along the fins, there exists temperature distribution, which makes different melting rate and inclines the solid-liquid interface. The gradient of the interface becomes steeper as the temperature of heating surface decreases. This phenomenon can be explained qualita-



(a) $\Delta T_w=7$℃



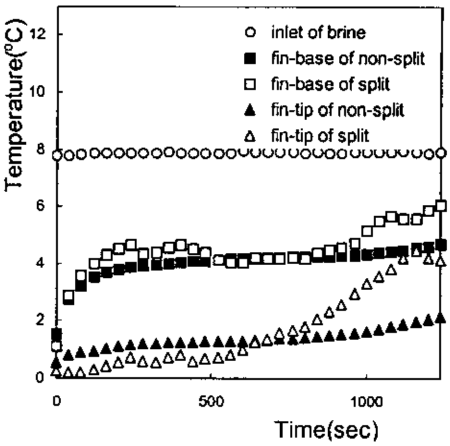
(b) $\Delta T_w=20$℃

Fig. 5 Photographs of melting process.

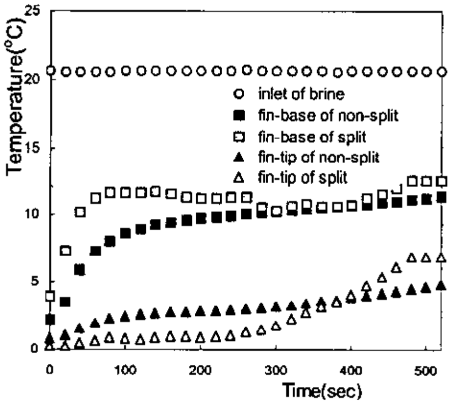
tively as follows. If the temperature of heating plate is not high, the temperature near fin-tip remains at the melting point and the melting does not proceed at all, which can be observed till 200s in Fig. 5 (a). This means that the heat from the heating plate is absorbed into the ice on the way and does not transfer to the fin tip. On the other hand, if the temperature is sufficiently high, the entire fin surface maintains over a melting point except the period melting starts immediately. Therefore, when the temperature is too low and the fin is too long, no melting occurs near the fin tip, and the ice is fixed in the chamber and cannot rotate to contact the fin surface. The uppermost photograph in Fig. 5 (a) is just the case. Figure 6 of timewise temperature variation shows that the fin-tip temperature approaches the melting point till the half time of total melting elapses.

Though this result is obtained in limited experiments, it has an important meaning. At the ice storage system for indoor cooling, the temperature of water used usually as a working fluid to transfer heat from the storage tank to the load becomes about 10℃. Hence, the heating plate maintains at the temperature lower than 10℃ and the patterns at Fig. 5 (a) can appear in the actual system. At the same temperature, the solid-liquid inclination is much steeper at ice than octadecane because thermal properties are different.

The heat flux q determining the melting rate in the direct contact melting is strongly dependent on the temperature difference ΔT between heating surface and melting point if other parameters are fixed. The heat flux ratio q_t/q_w of fin-tip to fin-base is determined by the ratio $\Delta T_t/\Delta T_w$ of the temperature difference. The inclination solid-liquid interface varies according to the heat flux ratio.



(a) ΔT_w=7℃



(b) ΔT_w=20℃

Fig. 6 Timewise variation of temperature.

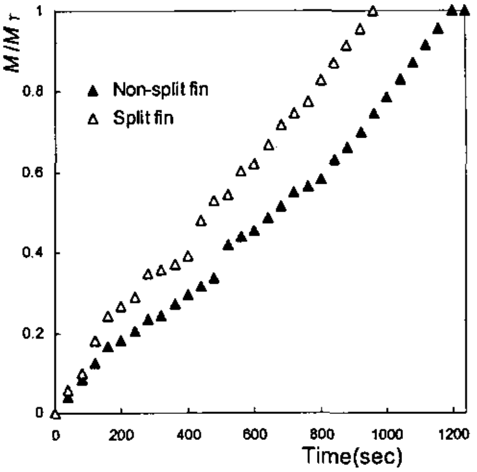
The condition under which the fin is situated in the present problem considerably differs from that of traditional fin problems well introduced in texts. The convection heat transfer coefficient is assumed to be constant, but the coefficient in the present problem differs between the upward and downward surfaces, though the former can approximately be treated as adiabatic because the heat transfer coefficient dominated by natural convection is very small comparing to that by direct contact melting. Moreover, the surface temperature influences the heat transfer coefficient h in direct contact melting; thus, h varies as $h \sim \Delta T^{-0.25}$ along the fin surface with the temperature distribution. Nevertheless, it may be meaningful to use the results obtained under such a simple situation in order to explain this phenomenon qualitatively. The temperature distribution along one-dimensional fin under the condition that the fin is of finite length and loses heat by convection from its end can be expressed by

$$\frac{T-T_0}{T_w-T_0}=\frac{\cosh m(L-x)+\left(\frac{h}{mk}\right)\sinh m(L-x)}{\cosh mL+\left(\frac{h}{mk}\right)\sinh mL} \quad (1)$$

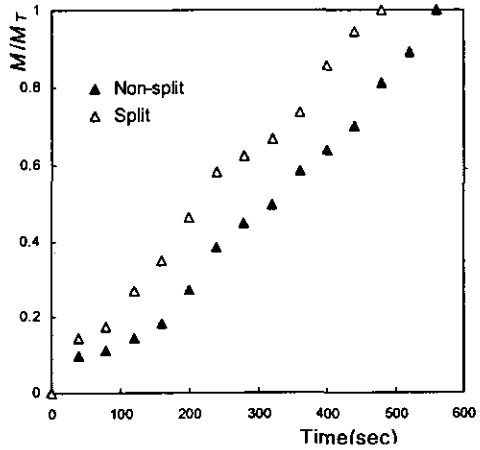
where $m=\sqrt{hP/kA}$, k is thermal conductivity of the fin; A is the cross sectional area of the fin and P is the perimeter, T_w is the temperature at the base of the fin and T_0 is that of surrounding fluid; L is the length of the fin. Rearranging equation (1), the fin-tip temperature T_t is represented by

$$\frac{T_t-T_0}{T_w-T_0}=\frac{1}{\cosh mL+\left(\frac{h}{mk}\right)\sinh mL} \quad (2)$$

Since the heat transfer coefficient h of direct contact melting is inversely related to the surface temperature, the average value of h increases as the temperature of the heating plate (correspondingly the average temperature of the fin surface) decreases, in turn, m in equation (1) becomes larger and the right-hand side of equation (2) decreases. Accordingly, the ratio of ΔT at fin-tip to ΔT at fin-base decreases and consequently the melting rate falls down near the fin-tip and the solid-liquid interface is further inclined.



(a) $\Delta T_w=7$℃



(b) $\Delta T_w=20$℃

Fig. 7 Timewise variation of melting fraction.

The melting rate was obtained by graphically analyzing the photographs along the solid-liquid contour. Figure 7 shows melting amounts with elapse of time. In the figures, the ordinate variable is the ratio M/M_T, where M is the mass melted between the start of melting and an elapsed time t, and M_T is the initial mass of the ice in the space enclosed by two fins. It is obvious that the melting rates are higher for split than for non-split fin and there does exist the effect of the split no matter what a heating plate temperature is. This is the effect of split fin, that is, the melted liquid passes the gap of the split fin and the average melt travel distance becomes shorter. By inclining the main body at 4°, the contact melting occurs on the heating plate as well as the fin surface.

4. Conclusions

In order to apply the heating plate with split fins to the ice storage tank, we used the ice as specimen of latent thermal storage material. First of all, it may be valuable that the ice was used in the experiments as the specimen owing to difficulties on volumetric expansion and severe void inclusion. It is obvious that the melting rate increases for split fins comparing to non-split fins. Nevertheless, application of the heating plate with split fins requires additional researches in an actual ice storage system. That is, the direct contact melting does not occur well in the range of temperature usually used. At the same temperature, the solid-liquid inclination is much steeper at ice than octadecane because thermal properties are different. So far as it is not used a smaller chamber than that by this experiments or another device, the natural convection-driven melting is dominated and the object cannot be attained to enhance the heat flux by the direct contact melting.

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