PERGAMON

International Journal of Heat and Mass Transfer 42 (1999) 2981–2990

International Journal of HEAT and MASS TRANSFER

Experiments on melting of slush ice in a horizontal cylindrical capsule

Tsuyoshi Kawanami, Shoichiro Fukusako*, Masahiko Yamada, Kenji Itoh

Division of Mechanical Science, Graduate School of Engineering, Hokkaido University, Sapporo 060-8628, Japan

Received 16 July 1997; in final form 22 September 1998

Abstract

Melting of slush ice in a horizontal cylindrical capsule has been investigated experimentally to determine the interaction of fluid flow induced by both motion of the slush ice and free convection owing to thermal and concentration diffusion. The slush ice, which is a mixture of fine ice particles and ethylene glycol aqueous solution, was utilized as a testing material and was heated by the capsule wall. During the melting process the slush ice is drawn by buoyancy to the top of the heated capsule where close-contact melting occurs. Melting behavior and melting rate of the slush ice were observed and measured for parameters such as initial concentration of aqueous binary solution and heat flux. The results revealed that the melting heat transfer of slush ice is markedly effected by free convection in the double-diffusive layers arose from the thermal and solutal buoyancy forces.

Nomenclature

C concentration of aqueous binary solution [mass%]
C_i initial concentration of aqueous binary solution [mass%]
D inner diameter of cylindrical capsule [m]
h average heat transfer coefficient [W m^{-2} K^{-1}]
h_ϕ local heat transfer coefficient [W m^{-2} K^{-1}]
I.P.F. ice packing factor (= mass ratio of ice to ethylene glycol aqueous binary solution) [mass%]
L latent heat [kJ kg^{-1}]
q heat flux of heated wall [W m^{-2}]
T temperature in vessel [°C]
T_b temperature of slush ice [°C]
T_f fusion temperature [°C]
T_s local temperature of slush ice [°C]
$T_{w\phi}$ local temperature of heated wall, [°C]
t elapsed time from start of melting [min]
W_i initial mass of ice in test vessel [kg]
W_m mass of melted ice [kg]
Y distance from top of cylindrical capsule [m].

Greek symbols
ρ_i density of ice [kg m^{-3}]
ρ_w density of water [kg m^{-3}]
ΔV volumetric shrinkage owing to melting [m^3]
$\Delta V'$ expanded volume of melted liquid owing to sensible heat [m^3].

1. Introduction

Melting phenomena are related to a wide variety of engineering fields: purification of metals, welding, electroslag melting, thawing of moist soil, and latent heat-of-fusion thermal-energy storage are a few of important applications which have motivated research in this area.

Melting is a phase transformation process that is accompanied by absorption of thermal energy. The essential feature of the systems that exhibit melting phenomena is the existence of a liquid–solid interface that separates the two phases containing different thermophysical properties and the absorption of thermal energy at the interface. The major problem in melting is thus to determine transport phenomena of the latent and sensible heat of the system. There is quite a large body of literature concerning a variety of such problems in engineering as well as in the applied sciences. Recent reviews summarize prior work in this area [1–8].

In previous studies pertaining to melting of a solid contained in a confined vessel, consideration has been given to either to a melting solid which is constrained to

* Corresponding author. Tel.: +81 011-706-6424; fax: +81 011-706-7889.

0017–9310/99/$ - see front matter
PII: S0017-9310(98)00340-8

prevent its possible movement owing to gravity or to a solid which is free to fall under gravity [8]. In the first case, the melting solid is maintained at a fixed position inside the vessel throughout the melting process, then is completely surrounded by the liquid melt, and the energy needed for the melting is transported from the heating wall to the solid–liquid interface by free convection within the liquid melt. In the second case, the solid is free to respond to the net force acting on it. If the solid phase has higher density than the liquid phase the solid sinks to the bottom of the vessel. On the contrary, if the solid phase is lighter than the liquid phase the unmelted solid is drawn by buoyancy to the top of the vessel. In either case, a region of close-contact melting arises between the solid and the heating wall.

Utilization of thermal-energy storage system for air conditioning has recently evoked energy saving and normalizing the requirement level of the electric power supply [9, 10]. For conventional ice-storage systems using a pure ice system as a phase change material (PCM) it has been pointed out [11–14] that the melting heat transfer performance may be reduced with time because the melting ice surface is separated more far from the heat transfer wall.

Marked attention has recently been given to a slush ice [15, 16], which is essentially a mixture of fine ice particles and aqueous binary solution, as a new PCM in place of common ice owing to demand of both high efficient ice producing and regulate handling of melting heat transfer performance as well as transportability. With respect to the melting heat transfer performance in releasing the cold thermal energy from the slush ice, the melting characteristics of a quiescent slush ice around a horizontal heated tube [17] and in a rectangular capsule with a vertical heated wall [18] as well as with a top heated wall [18] were determined experimentally.

In addition, a solid–gas–liquid three-phase fluidized bed heat exchange system [19] and a direct contact heat-exchange system, in which the slush ice is operated as the fluidized bed, was proposed for releasing the cold thermal energy. Detailed basic data on the melting characteristics of the slush ice are highly required for developing high efficient heat exchanger using the slush ice. However, there seems to be a variety of unknown characteristics on the melting mechanism as well as the melting behavior for releasing both efficiently and regulatively the cold thermal energy from the slush ice.

This paper reports a study on the melting characteristics of slush ice in a horizontal cylindrical capsule. In order to inspect the local heat transfer coefficient distribution in circumference direction in detail, the capsule wall was electrically heated to be a constant heat flux condition. Experimental runs were carried out to investigate the effects of heat flux and initial concentration of aqueous binary solution on both the melting behavior and the heat transfer characteristics of the slush ice. Photographs of flow patterns are presented, and dependence of the double-diffusion on the flow structure is discussed. The results obtained form present study have great importance and usefulness not only for design of the high efficient heat exchanger using the slush ice, but also for operations of the thermal energy storage system.

2. Experimental apparatus and procedure

2.1. Test apparatus

The experimental apparatus consists essentially of a test section, a cooling-brine circulating loop, an electric supplying system, optic systems, and associated instrumentation. The test apparatus is schematically depicted in Fig. 1. The test cylindrical vessel is a lucite tube of 100 mm inner diameter with 69 mm length. In order to enable observation of the phenomena within the vessel the cylindrical vessel was enclosed at the ends by 9.6 mm-thick double-pane glass disks which were tightened against rubber affixed to the lucite tube. A lucite disk of 900 μm in thickness in place of one of the double-pane glass disks was adopted when the distribution of the temperature within the test vessel by use of the thermoviewer. An additional charging chamber, which is filled with the material identical to testing slush ice and may compensate volumetric shrinkage of the testing material based on melting process, was prepared.

Figure 2 shows schematically the details of the heated wall, which consists of both main and guard heaters. The heaters are made up of lucite tube on which stainless sheet of 25 μm in thickness are affixed, and the surface of the heaters was electrically insulated using a thin coat

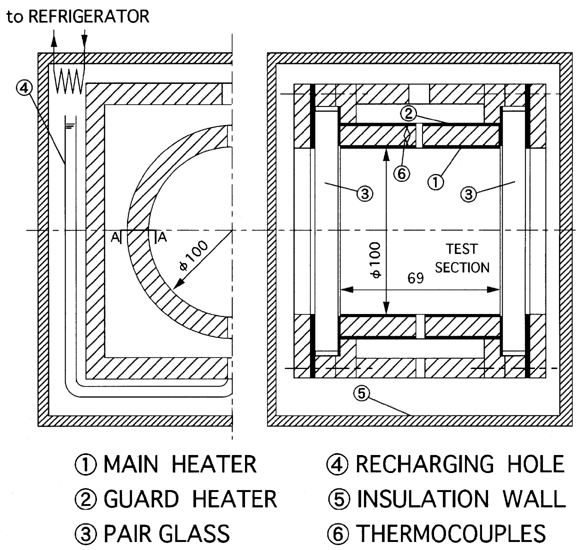

Fig. 1. Schematic of experimental apparatus.

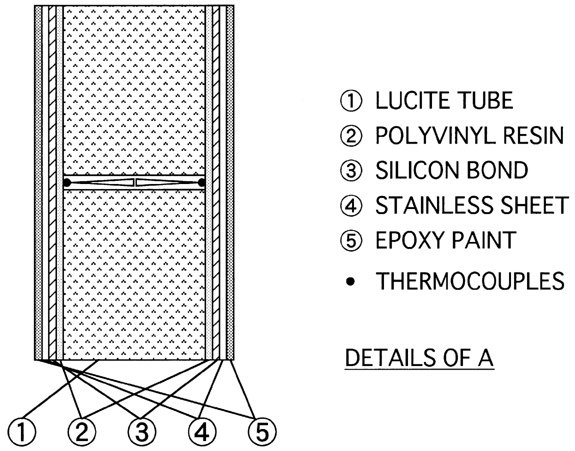

Fig. 2. Details of main and guard heaters.

of the epoxy paint. To measure the surface temperature of the main heater, 24 C–A thermocouples (0.1 mm diameter) with 15° intervals were situated between the main heater and the inner wall of tube. Moreover, additional 20 C–A thermocouples were attached between the outer wall of tube and the guard heater to measure the temperature of the guard heater. A long small slender shielded probe (a stainless tube with 0.81 mm diameter) with thermocouples was traversed vertically from the top of the tube to measure the temperature distribution within the slush ice. In addition, qualitative measurement of the temperature distribution within the test vessel was performed by use of a thermoviewer (Nihon Denshi; JTG-3100). The test vessel was set in a temperature-regulated room, as indicated in Fig. 1.

2.2. Test procedure

To prepare the slush ice possessing the prescribed ice-packing-factor and initial concentration of solution, a liquid–solid mixture, which consists of both fine ice particles (average 500 μm diameter sphere) obtained by use of the screens and ethylene glycol aqueous binary solution adjusted to fixed temperature and concentration, was adopted as a testing slush ice. The ice-packing-factor (I.P.F.) of the testing slush ice was 65 mass% through all of the experiments. Four values of initial solution concentration of 5, 10, 20 and 30 mass% were set in the experiments.

Before the experimental run, the temperature of the test vessel was maintained at slightly less than fusion temperature of the aqueous binary solution to avoid melting of the slush ice. Then the testing slush ice was charged in the test vessel. The start of the experiment was defined as when the electric power input was initiated. As shown in Fig. 2, the guard electric power input was adjusted so that no temperature difference between the main and guard heaters is detected to avoid the heat loss from the main heater. The heat fluxes was set at 8.0×10^2, 1.6×10^3, and 2.4×10^3 W m^{-2}, and also the temperature in the temperature-regulated room (see Fig. 1) was carefully adjusted to be at the mean temperature between the slush ice and the melt pool to minimize the heat loss from the test vessel. During the course of the experiment, both the shape of the melting surface and the flow patterns within the melt were observed and photographed by a shadowgraph method using a He–Ne gas laser as the light source. In addition, the melting rate of the slush ice and local/average heat transfer coefficient at the heated wall were determined.

3. Data reduction

The essential quantities measured during the course of present investigation were vessel wall and slush ice temperatures, rates of melting, and electric power inputs. The procedure to evaluate local/average heat transfer coefficient at the cylindrical capsule wall is as follows;

The local heat transfer coefficient at the wall h_ϕ is defined as

$$h_\phi = q/(T_{w\phi}-T_b) \tag{1}$$

in which q is heat flux computed based on electric input, $T_{w\phi}$ is the local temperature along the cylindrical capsule wall, and T_b is the temperature of the slush ice which is assessed by averaging the temperature distribution within the slush ice layer. The average heat transfer coefficient is given by the next definition;

$$h = (1/\pi)\int_0^\pi h_{w\phi}\,d\phi \tag{2}$$

Mass of melted ice, which is closely related to volumetric shrinkage ΔV that is measured by the recharging volume of ethylene glycol aqueous solution in order to keep a fixed free surface at the level gauge on the recharging chamber (see Fig. 1), can be evaluated as follows:

$$W_m = (|\Delta V| + \Delta V')\times(\rho_w\times\rho_i)/(\rho_w-\rho_i) \tag{3}$$

in which $\Delta V'$ is the expanded volume of the melt owing to sensible heat that is estimated by both the mean surface temperature of the capsule wall and the temperature of the slush ice, ρ_w is the density of water, and ρ_i is the density of ice.

4. Results and discussion

4.1. General observation of melting

A typical melting process against the time is shown in Fig. 3, where the three sequential characteristics were

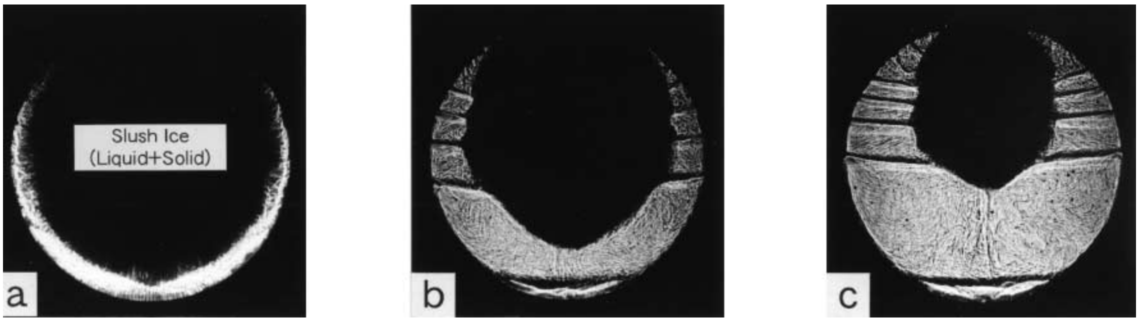

Fig. 3. Melting behavior for $C_i = 20$ mass% and $q = 2.4 \times 10^3$ W m^{-2}: (a) $t = 5$ min; (b) $t = 15$ min; (c) $t = 25$ min.

reproduced from the photographs, which were obtained by shadowgraph method. Because of its lower average density the unfixed slush ice rises to the top of the cylindrical capsule where good thermal contact with the heated wall results in intensive melting. The upward motion of the slush ice causes the new melt to be squeezed out of the gap between at the close-contact region into the melt pool below. It was quite difficult to photograph the liquid film separating the slush ice from the top of the capsule as the gap was too thin to be detected.

Inspection of the figure reveals that there take place stratified layers in the melt pool between slush ice and capsule wall, which are resulted from a coupled heat and concentration transfer, as discussed in detail later. In addition, it may be seen in Fig. 3 that channel segregates owing to plume containing solute-rich liquid issuing from the mush (slush ice)–melt interface (see the bottom portion of the melting slush ice in Figs. 3(c) and 5).

Figure 4 illustrates schematically a somewhat complicate mechanism of melting, which will now be explained as follows.

(1) As shown in Fig. 4(a), the slush ice is pressed by buoyancy against the top of the heated capsule wall. However, direct contact between the upper portion of the slush ice and the wall is not achieved owing to the continuous production of melt by the melting slush ice, a quite thin, liquid-filled gap necessarily exists between the slush ice and the capsule wall. The liquid produced by melting is continuously squeezed out of the gap by the force of buoyancy which presses the slush ice against the top of the capsule. The energy needed for the melting of the slush ice which borders the gap is transported by conduction across the gap. In addition to what was mentioned above, it is to be noted that some part of the melt is squeezed into the slush ice, which consequently results in an issuing of the solute-rich liquid from chimney at the bottom of the melting slush ice (see Fig. 5).
(2) As indicated in Fig. 4(b), the heat transport is dominated by thermal conduction in the initial stage of the melting, then the potentially stable concentration distribution may be formed in the melt region after some mixing process between the melt water being produced by melting of the slush ice and the ethylene glycol aqueous solution.
(3) As illustrated in Fig. 4(c), free convection occurs as time elapses. Then, a number of stratified layers, which are based on double diffusion, are formed (cf. [20, 21]) in the melt between the slush ice and the heated wall (see Figs. 3 and 5). It was observed that the number of stratified layers increases with increasing initial concentration of the aqueous binary solution as well as decreasing heat flux at the wall.
(4) During the course of the melting the solute-rich liquid tends to issue out of the bottom of the slush ice because the melt liquid seeps downwards within the liquid slush (see Fig. 3(b) and (c)). Hence the temperature at the exit of the chimney decreases less than the fusion temperature of the solute-poor melt fingering near the bottom mush–melt interface, which causes the formation of the dendritic frozen layer (see Fig. 4(d)).

4.2. Melting behavior and temperature distribution in vessel

Figure 5 indicates the effect of heat flux on both the melting behavior and the temperature distribution in the vessel, which were respectively obtained by use of a shadowgraph method and a thermoviewer. It is seen in the figure that the number of the stratified layers decreases with an increase in heat flux, which results in a variety of the shapes of the melting interface. This fact may be due to the following reason: the thermal buoyancy force increases with increasing heat flux because of increasing temperature of the melt liquid in the vicinity of the heated wall; then the equilibrium point between the thermal buoyancy and the solutal buoyancy force moves

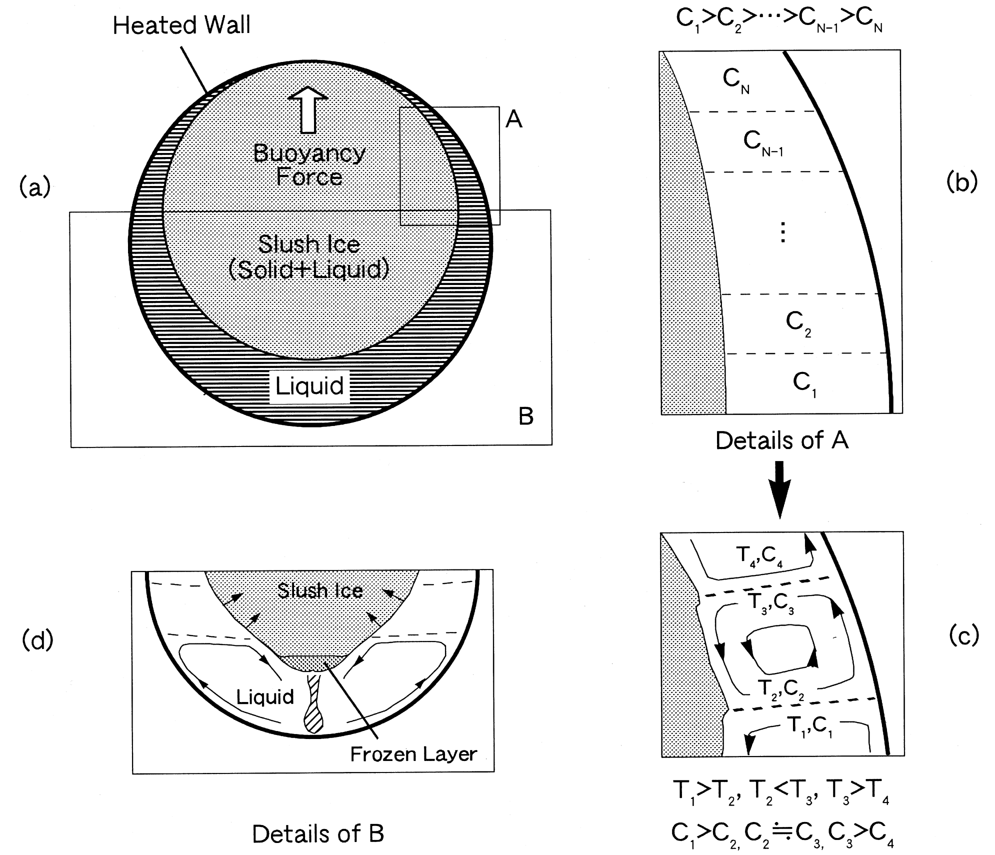

Fig. 4. Melting mechanism.

upwards; a decrease in number of the stratified layers, which corresponds to an increase in distance between the stratified layers, results in the difference in intensity of the free convection. In addition, it is observed that the flow rate of the solute-rich melt issuing out of the bottom of the slush ice as well as the rate of dendritic ice formation increases with an increase in heat flux. This may be caused by increasing seepage of melted liquid into slush ice owing to increasing heat flux.

It is seen from the temperature distribution (see Fig. 5(d), (e), and (f)) that the temperature in the melt liquid in the vessel markedly changes owing to increasing heat flux. This may be resulted from the fact that increasing heat flux causes decrease in the number of the stratified layers, increase in temperature of the wall, and then increase in free convection intensity. On the contrary, the temperature in the slush ice decreases with an increase in heat flux. This may be explained by considering that increasing heat flux results in increasing melting rate and then decreasing concentration diffusion in the slush ice, namely, the concentration diffusion in the slush ice slackens with increasing melting velocity owing to increasing heat flux.

4.3. Temperature distribution in slush ice

4.3.1. Transient temperature distribution

Figure 6 shows transient temperature distributions along the center line from the top to the bottom in the slush ice for $C_i = 20$ mass% and $q = 8.0\times10^2$ W m^{-2}. The general feature through the data is that the temperature in the slush ice decreases monotonically as the distance from the top heated wall where close-contact melting occurs, and then sharply increases near the bottom of the slush ice.

The highest temperature in the vicinity of the heated wall may be attributed to the fact that the melt liquid with low concentration is squeezed into the slush ice, which causes the aqueous binary solution with high concentration to flow down through the slush ice. Inversely, near the lower mush-melt interface (near the bottom of the slush ice) the melt liquid with low concentration tends to be stagnant and hence to diffuse into the slush ice from the melt (see Fig. 4(d)), then the temperature of the slush ice near the mush–melt interface (the bottom of the slush ice) may evidently increase. Besides the facts mentioned above, discharging of the aqueous binary solution with high concentration results in gradual increase in mean temperature through the slush ice.

4.3.2. Effect of heat flux

In Fig. 7, the effect of heat flux on the temperature in the slush ice at the heat input of 2.4×10^6 J m^{-2} is depicted. The figure indicates that reducing in the heat flux causes increasing in the temperature in the slush ice. This may be due to the following fact; the melting time increases with a decrease in heat flux, which results in increasing melt liquid with low concentration that seeps into the slush ice and then that discharges out of the bottom of the slush ice.

4.3.3. Effect of initial concentration of solution

Figure 8 shows the effect of initial concentration of binary solution on the temperature distribution in the slush ice for $C_i = 5$, 10, 20 and 30 mass%. It is seen in the figure that increasing initial concentration of solution causes decreasing temperature in the slush ice as well as increasing temperature difference between the maximum and the minimum values in the slush ice. An increase in initial solution concentration reduces the equivalent freezing temperature of the slush ice and then promotes the temperature difference between the melt liquid seeping into the slush ice and the binary solution within the slush ice. This may be one of the reasons for the temperature characteristics mentioned above.

4.4. Characteristics of local heat transfer coefficient

The detailed variation of the local heat transfer coefficient as a function of location along the heated wall are shown in Fig. 9, in which total heating rate $(q \times t)$ is identical for all the data. The abscissa is angle in radian from the top of the testing vessel. The general feature through the data is that the local heat transfer coefficient sharply decreases for ϕ between 0 and $\pi/4$, and then gradually decreases with local/cyclic increase and decrease. The sharp decrease for ϕ from 0 to $\pi/4$ may be due to the fact that the melt thickness (i.e., distance between the slush ice and the heated wall) increases with increasing ϕ, thus resulting in increasing thermal resistance. Local/cyclic increasing and decreasing for ϕ greater than $\pi/4$ may be resulted from both the formation of stratified layers and the free convection between the stratified layers. The difference in heat transfer coefficient with different value of q at the top of the vessel ($\phi = 0$) where close contact melting occurs may be explained by considering that the latent heat based on the melting of ice particles suppresses the temperature increase of the heated wall owing to increasing heat flux. Namely, increasing of the temperature difference defined as $(T_{w\phi} - T_b)$ is quite small in comparison with increasing of the heat flux. As a result, the local heat transfer coefficient calculated by eqn (1) increases with an increase in heat flux.

4.5. Characteristics of average heat transfer coefficient

4.5.1. Effect of heat flux

Consideration will now be given to the characteristics of the average heat transfer coefficient. Figure 10 indicates the effect of heat flux at the heated wall on the average heat transfer coefficient, h, for three values of heat fluxes, 8.0×10^2, 1.6×10^3, and 2.4×10^3. The abscissa denotes the amount of heat added to the slush ice during the time t. From Fig. 10, the average heat transfer coefficient sharply decreases at the initial stage of melting, keens approximately constant or quite slightly decreases, and then decreases again, with time.

The decrease in the value of h at the initial stage of melting may be attributed to a sharp increase in temperature of the heated wall owing to increasing distance between the slush ice and the heated wall. Meantime, onset of free convection in the melt liquid enhances the heat transfer, which may result in a quite slight decrease in the heat transfer coefficient with the time. The decrease in h at the final stage of melting may be resulted from the following fact: the buoyancy force acting on the slush ice decreases and close-contact area at the top of the vessel decreases, causing an increase in the temperature of the upper past of the heated wall.

On the contrary, the value of h increases with an increase in heat flux. This may be due to the fact that an increase in heat flux enhance natural convection, and then an increase in temperature of the heated wall is suppressed.

4.5.2. Effect of initial concentration of solution

The effect of initial concentration of solution on the average heat transfer coefficient, h, against the time is presented in Fig. 11. The major tends of timewise variations of h for $C_i = 5$, 10, 20 and 30 mass% appear to be quite similar to those in Fig. 10. However, it is seen in Fig. 11 that the values of h at the range of abscissa from 80–120 min for $C_i = 5$ and 10 mass% considerably decrease unlike those for $C_i = 20$ and 30 mass%. This may be resulted from increasing temperature in the slush ice during the melting time with an increase in initial solution concentration. In addition, increase in initial concentration reduces the average heat transfer coefficient, which may be due to the following fact; as the initial solution concentration increases, both the number of the stratified layers and the viscosity of the melt liquid increase, which eventually may suppress the free convection in the melt; the temperature of the top of the

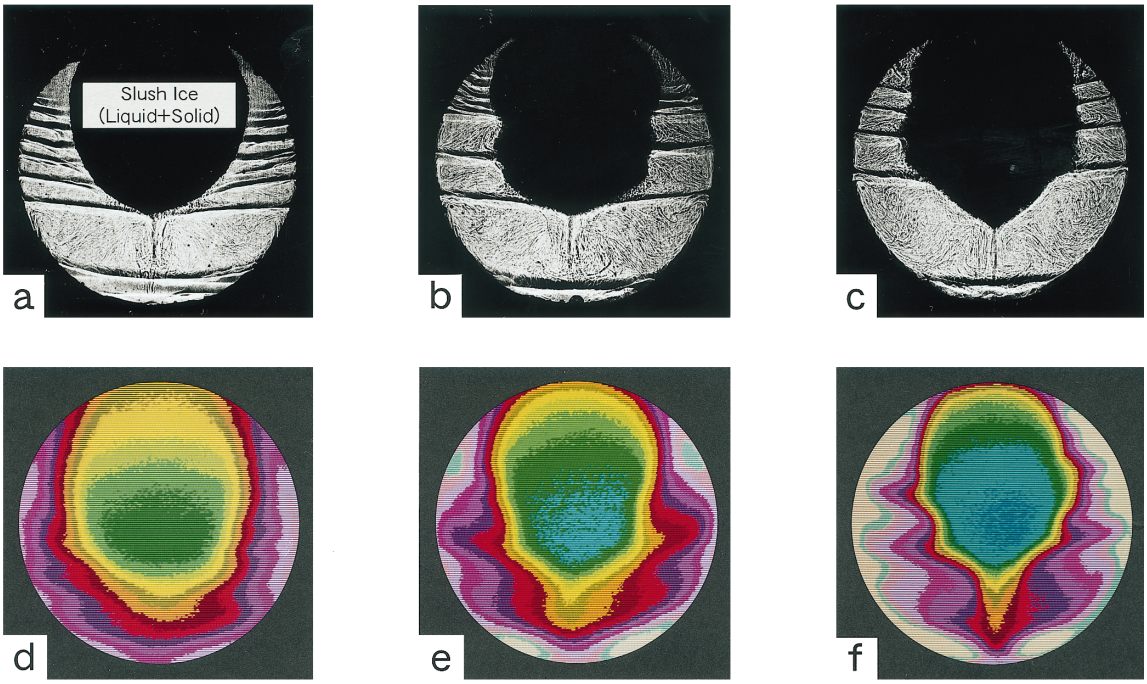

Fig. 5. Melting behavior and temperature distribution for $C_i = 20$ mass% and $q \times t = 2.88 \times 10^6$ J m^{-2}: (a), (d) $q = 8.0 \times 10^2$ W m^{-2}; (b), (e) $q = 1.6 \times 10^3$ W m^{-2}; (c), (f) $q = 2.4 \times 10^3$ W m^{-2}.

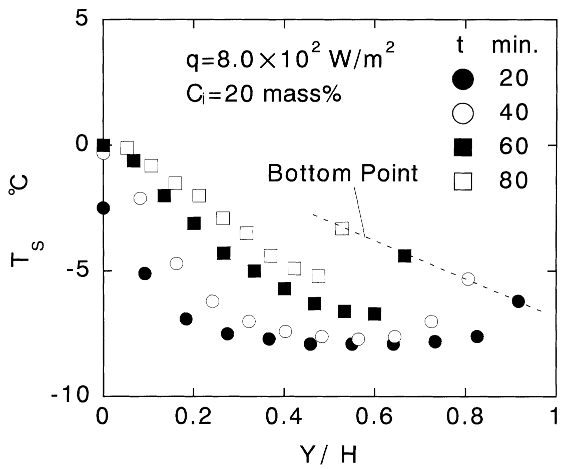

Fig. 6. Slush ice temperature.

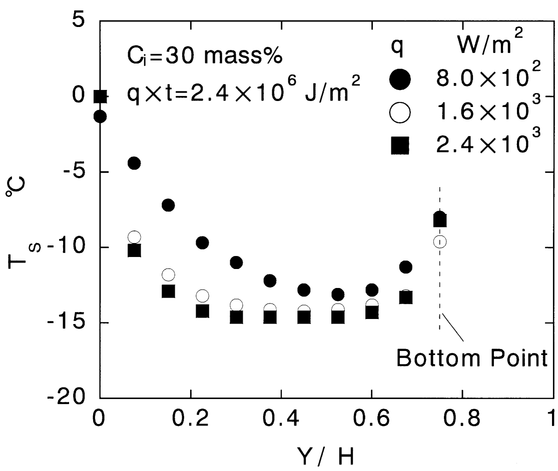

Fig. 7. Effect of heat flux on slush ice temperature.

heated wall where close-contact melting occurs is approximately constant irrespective of initial solution concentration, while the average temperature in the slush ice decreases with an increase in initial concentration of solution.

4.6. Melting rate

4.6.1. Effect of heat flux

Figure 12 shows the effect of heat flux on the melting rate of slush ice. The ordinate denotes the ratio of the

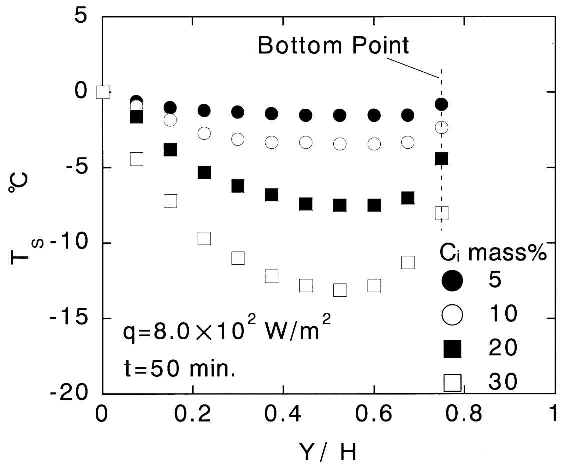

Fig. 8. Effect of initial concentration of solution on slush ice temperature.

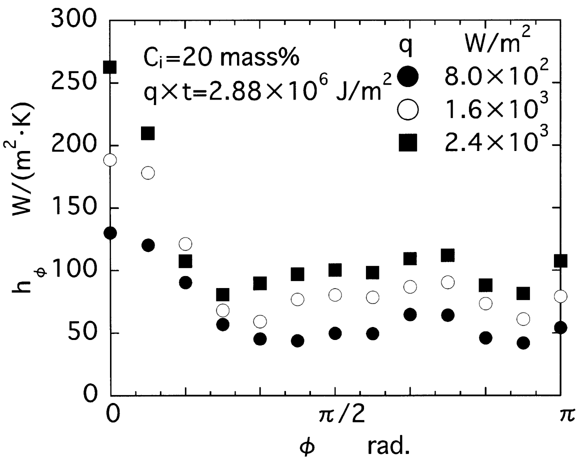

Fig. 9. Effect of heat flux on local heat transfer coefficient.

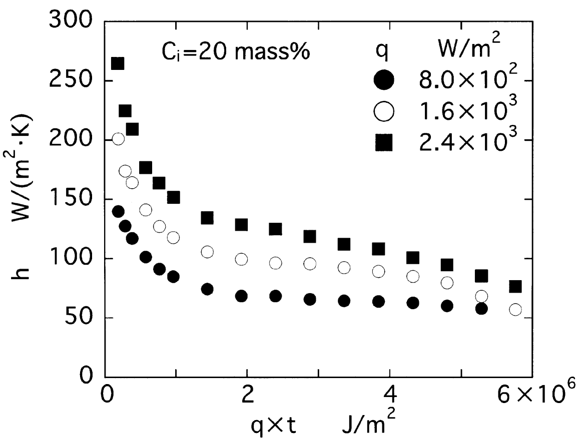

Fig. 10. Effect of heat flux on average heat transfer coefficient.

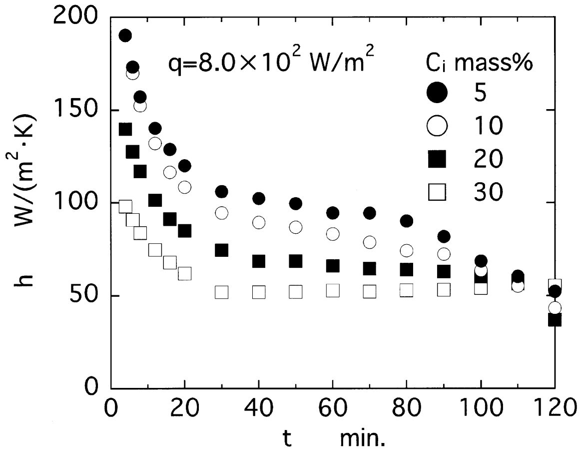

Fig. 11. Effect of initial concentration of solution on average heat transfer coefficient.

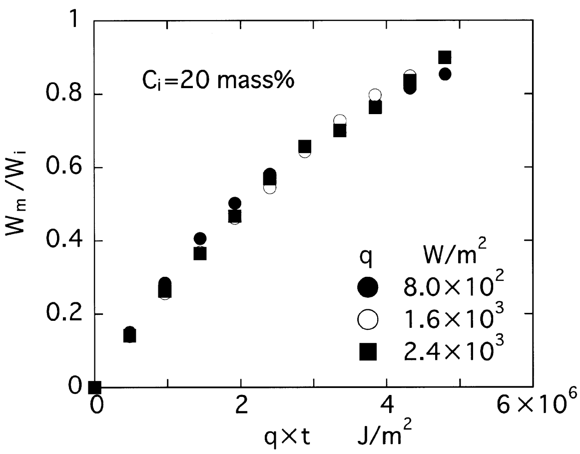

Fig. 12. Effect of heat flux on melting rate.

mass of melted ice W_m to initial mass of ice charged in the vessel W_i before the test run. The abscissa indicates the amount of heat supplied during the time t. The melting rate increases monotonically as the time advances, while the increasing rate gradually decreases. This may be due to the fact that close-contact area between the slush ice and the heated wall tends to decrease as time elapses. On the other hand, it was obtained from the results that the melting rate was not affected by heat flux. It may be considered that almost all of the heat input from the heated wall is not spent as sensible heat for the increasing of the melted liquid temperature but as latent heat for the melting of the slush ice.

4.6.2. *Effect of initial concentration of solution*

The effect of initial concentration of solution on the melting rate of slush ice is demonstrated in Fig. 13. From

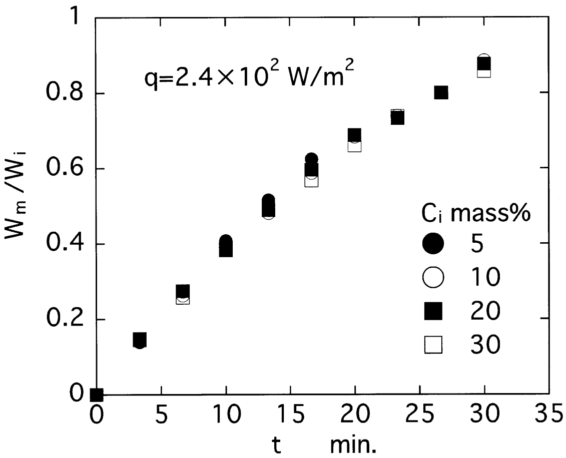

Fig. 13. Effect of initial concentration of solution on melting rate.

the figure, it seems that the melting rate may be hardly influenced by a variation of the initial concentration of solution. The reason for this phenomenon may be considered the following effects which are contrary to each other: the latent heat of fusion of the slush ice decreases with increase in the initial concentration of solution due to the decrease in the equilibrium temperature of the solution (see Fig. 14), thus resulting in an easy melting of the slush ice; increasing initial solution of concentration causes an obstruction of the free convection due to the increasing of the viscosity of the melt layer and of the number of the stratified layers, therefore, temperature of the melt layer for 20 mass% is about 2.5°C higher than that for 5 mass% because of the heat flux which is mostly

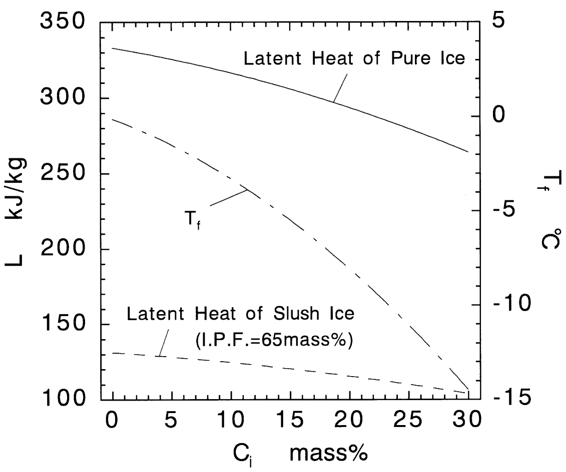

Fig. 14. Latent heat of ice in aqueous solution.

utilized to increase the liquid temperature as sensible heat.

5. Conclusions

Experiments were performed to determine the melting characteristics of slush ice in a horizontal cylindrical capsule. The following conclusions may be drawn within the experimental range of parameters covered in the present work.

(1) During the melting process the slush ice is drawn by buoyancy to the top of the heated capsule where close-contact melting occurs, which results in intensive melting. The upward motion of the slush ice causes the new melt to be squeezed out of the gap at the close-contact region into the melt.
(2) As the time advances, the free convection is generated, by which a number of stratified layers are formed in the melt between the slush ice and the heated wall. The shape of the melting interface is markedly influenced by both the location and height of the stratified layer as well as the number of the stratified layers.
(3) The local heat transfer coefficient is greatest at the top of the vessel and tends to decrease along the vessel wall with local/cyclic variation due to the stratified layers and the free convection. The average heat transfer coefficient increases with an increase in heat flux, while it decreases with decreasing initial solution concentration.
(4) The melting rate of the slush ice increases monotonically as a function of melting time, irrespective of the heat flux and initial solution concentration.

References

[1] R. Viskanta, Natural convection in melting and solidification, in: S. Kakac, W. Aung, R. Viskanta (Eds.), Natural Convection: Fundamentals and Applications, Hemisphere, Washington, 1985, pp. 845–877.
[2] S. Fukusako, N. Seki, Heat transfer problems on ice and snow, in: K.C. Cheng and N. Seki (Eds.), Freezing and Melting Heat Transfer in Engineering, Hemisphere, Washington, 1991, pp. 341–389.
[3] R. Viskanta, Heat transfer during melting and solidification of metals, Transactions of the ASME Journal of Heat Transfer 110 (1988), 1209–1219.
[4] L.S. Yao, J. Prusa, Melting and freezing, Advance in Heat Transfer 19 (1990) 1–95.
[5] R. Viskanta, Mathematical modeling of transport processes during solidification of binary systems, JSME International Journal Series II 33 (1990) 409–423.
[6] S. Fukusako, N. Seki, Fundamental aspect of analytical and numerical methods on freezing and melting heat-trans-

fer problems, Annual Review of Numerical Fluid Mechanics and Heat Transfer 1 (1987) 351–402.
[7] S. Fukusako, M. Yamada, Recent advances in research on water-freezing and ice-melting problems, Experimental Thermal and Fluid Science 6 (1993) 90–105.
[8] S. Fukusako, M. Yamada, Recent advances in research on melting heat transfer problems, Proceedings of the 10th International Heat Transfer Conference, 1994.
[9] A. Miyasaka, Current trends of ice storage system in the U.S.A., Refrigeration 62 (1987) 82–392 .
[10] Y. Yanagihara, An economic study of ice storage type HVAC systems, Refrigeration 62 (1987) 487–497.
[11] H. Rieger, H. Beer, The melting process of ice inside a horizontal cylinder: effects of density anomaly, Transactions of the ASME Journal of Heat Transfer 108 (1986) 166–173.
[12] K. Torikoshi, Y. Nakazawa, K. Kawabata, H. Yamamoto, K. Fushimi, An experimental study of melting of ice about horizontal cylinders, Proceedings of the Second International Symposium on Cold Regions Heat Transfer, 1989, pp. 45–50.
[13] K. Torikoshi, H. Yamashita, Y. Nakazawa, An experimental study of melting of ice about horizontal cylinders, Proceedings of the ASME/JSME Thermal Engineering Conference, vol. 1, 1991, pp. 269–274.
[14] T. Hirata, Y. Makino, Y. Kaneko, Analysis of natural convection melting inside isothermally heated horizontal rectangular capsule, Wärme- und Stoffübertragung 28 (1993) 1–9.
[15] M. Endo, M. Hoshino, Crystallized liquid ice thermal storage system, Refrigeration 62 (1987) 481–486.
[16] S. Fukusako, M. Yamada, Freezing characteristics of ethylene glycol solution, Wäme- und Stoffübertragung 24 (1989) 303–309.
[17] M. Yamada, S. Fukusako, H. Morizane, M.H. Kim, Melting heat transfer along a horizontal tube immersed in liquid ice, JSME International Journal 36 (1993) 343–350.
[18] S. Fukusako, M. Yamada, M.H. Kim, Melting heat transfer of liquid ice in a rectangular cavity with heated vertical wall, Proceedings of the Second JSME–KSME Thermal Engineering Conference, vol. 2, 1992, pp. 384–392.
[19] M. Yamada, S. Fukusako, H. Morizane, M.H. Kim, W. Schneider, Melting characteristics along a bundle of horizontal heated cylinders immersed in a liquid ice layer, Experimental Thermermal and Fluid Science 2 (1996) 305–312.
[20] C.J. Poplawsky, F.P. Incropera, R. Viskanta, Mixed Layer Development in a Double-Diffusive, Thermohaline System, Transactions of the ASME Journal of Solar Energy Engineering 103 (1981) 351–359.
[21] M.S. Christenson, F.P. Incropera, Solidification of an aqueous ammonium chloride solution in a rectangular cavity—I. Experimental study, International Journal of Heat and Mass Transfer 32 (1989) 47–68.