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Experimental Study of Heat Transfer in a Horizontal Melt Layer Heated at its Upper Wall

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Abstract

This paper is concerned with the free convective heat transfer in a melt layer of ice heated at its upper bounding surface. As water has its maximum density at 4°C, the onset of free convection occurs in the melt layer. Therefore, the melting rate of ice becomes more rapid because of the increased heat flux resulting from convection through the layer. From the experimental results, it is recognized that the heat flux q through the melt layer depends remarkably on the temperature of the upper surface T_1, but there is a region of an almost constant value of q in spite of the increased T_1. The ratio of the depth of convection layer to that of the entire melt layer, A, proposed by Katto et al.[9] is a useful parameter for the evaluation of the heat transfer in a melt layer. It is concluded experimentally that critical Rayleigh number associated with the onset of free convection varies from 1700 to 500 with the increased temperature of the upper wall surface.

Nomenclature

A = ratio of convection layer to entire melt layer depth,
g = acceleration of gravity,
h = depth of a convection layer,
H = depth of an entire melt layer,
$n = Nu/Nu_s$,
Nu = Nusselt number defined in equation (2),
$\overline{Nu}$ = modified Nusselt number defined in equation (4),
q = heat flux through a melt layer,
Ra = Rayleigh number defined in equation (3),
$\overline{Ra}$ = modified Rayleigh number defined in equation (5),
T_1 = temperature of an upper wall surface,
T_2 = temperature of lower wall surface, 0°C,
T_m = temperature of maximum density, 4°C,
ΔT = temperature difference,
α = heat transfer coefficient,
β = coefficient of thermal expansion (absolute value),
κ = thermal diffusivity,

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λ = thermal conductivity,
ν = kinematic viscosity.

1. Introduction

Numerous studies have been made on the melting of horizontal ice layer when the heat transfer in melt layer is simply conductive. For example, the analytical method by Neumann[1], the heat blalnce integral method by Goodman[2], the numerical method proposed by Murray *et al.*[3] are examples of methods presented so far. However, the ice layer does not always melt in a conductive mode but frequently in a convective mode.

The typical phenomena of convective heat transfer in a melt layer are shown as follows. Fig. 1 (a), (b) demonstrates two typical temperature fields in the melted water layer. In Fig. 1 (a), the temperature of the upper wall-surface T_1 is less than or equal to 4°C, but in Fig. 1 (b), T_1 is greater than 4°C. As water has its maximum density at 4°C, the liquid layer in Fig. 1 (a) and that corresponding to the range of 4°C at 0°C in Fig. 1 (b) are each unstable. When the depth of these unstable layers gradually increases in thickness with the lapse of the increasing time, the onset of free convection occurs in the melt layer. Consequently, the melting rate becomes suddenly rapid because of the increased heat flux through the layer.

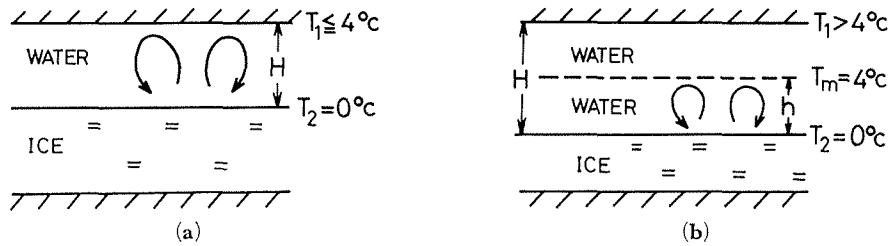


Fig. 1. Illustration of a melted water layer.

Recently, various studies of melting of a horizontal ice layer have been carried out under the condition that the layer melted from above with a heated rigid wall. For example, Boger *et al.*[4] reported that the convective heat transfer in the melt layer is similar to the experimental results reported by Silveston.[7] Yen[5] concluded that the convection heat flux for the case of melting from above was constant, independent of the temperature of the upper wall surface. However, their studies seem to be valid only under a restricted condition and do not provide satisfactory considerations of heat transfer for all cases of melting from above. Tien *et al.*[6] presented both their analytical and experimental results for the case of melting from below and concluded that the stable layer above an unstable layer in a melt layer retarded vortex motion and decreased the rate of heat transfer. However, strictly speaking, their conclusion seems to be somewhat inaccurate, and should be evaluated only when the ratio of the depth of stable layer to that of entire melt layer, A, is not $0<A<1$ but $A\simeq 1$ for the case of melting from above.

In the present study, convective heat transfer in a melt layer formed by the heating of upper plate is investigated in detail.

2. Experimental Apparatus and Procedure

Fig. 2 shows a total view of the present experimental apparatus used and Fig. 3 shows a schematic cross section. The main test chamber of $150 \times 150 \times 25$ mm^3 is constructed by using lucite plates with a thickness of 18 mm, except for one vertical side wall of the chamber, for which pairglass is used to obtain a more clear visual observation of various phenomena occuring in the chamber. A copper palte of 5 mm in thickness is used for the upper wall.

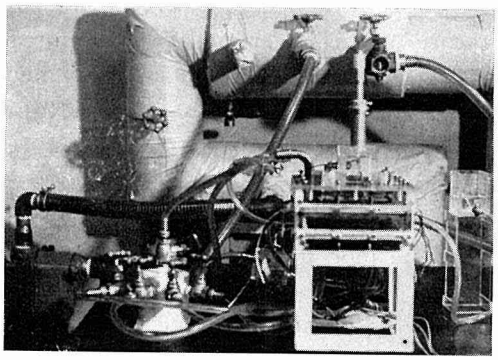


Fig. 2. Total view of the apparatus.

The temperature of the upper wall surface is uniformly maintained at constant by controlling the main heater and a guard heater attached to the outside. Bakelite plate of 1 mm in thicknees is embedded between the main and guard heaters.

As may be seen in Fig. 2, another small chamber of 20 mm in height, in which temperature controlled coolant is injected through copper pipes of 10 mm in diameter

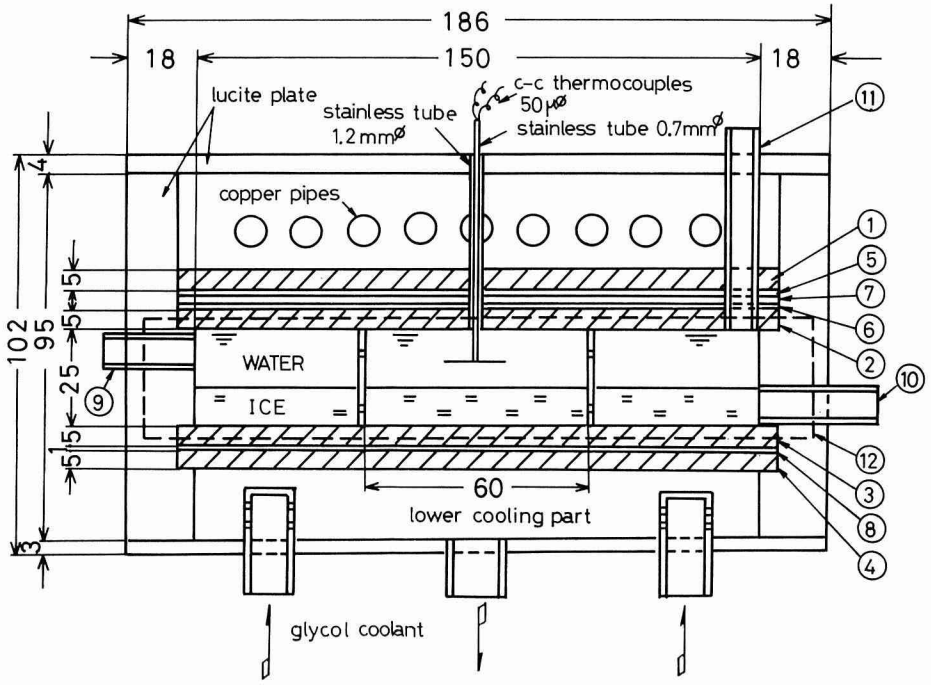


Fig. 3. Schematic cross-section of the test section.

in order to minimize the heat loss from the outside, is mounted on the main chamber.

The lower cooling wall used is a laminated bakelite plate of 1 mm in thickness which is sandwiched in between two copper plates of 5 mm in thickness. The temperature of the lower surface is uniformly kept at a constant temperature ($\leqq 0°C$) by injecting a temperature-controlled ethylen-glycol coolant into a cooling chamber under the main chamber.

An air-bubble free ice layer was successfully made when distilled and degassed water is gradually cooled. The temperatures of the upper and the lower wall-surface are measured by using a calibrated copper-constantan thermocouple 0.1 mm in diameter. These thermocouples are soldered onto each wall surface at an interval of 20 mm from the center. To check the heat loss from the side wall, aditional thermocouples are fixed onto the inner and the outer side-walls.

The temperature distributions in a melt layer are measured by copper-constantan thermocouple of 50 μ in diameter which is horizontally stretched to about 20 mm in length by using a bow-type thin piano wire.

Rate of one-dimensional heat fiow through the melt layer is evaluated by measuring the power of the main heater. Line current is fed into a voltage stabilizer which produces a constant output of 100 voltage. This output goes to a Variac by which the wattage is varied as required. The power input to the heating element is measured by using an ammeter and a voltmeter. Moreover, another method to evaluate the heat flow is carried out by measuring the temperature difference between the upper and lower surfaces of the bakelite plate sandwiched in the bottom cooling part. The deviation between the heat flow rates evaluated by both methods is within 5 percent or thereabouts in all of the present experimental runs. The entire apparatus is insulated by a styrofoam block of 50 mm in thickness.

The criterion of the onset of free convection in the melt layer is experimentally determined during the melting process. Before the onset of free convection, it is found that the temperature distribution in the layer tends to be almost linear since the interfacial melting velocity is very slow. This fact may indicate that the experimental system reaches a quasi-steady state thermally and hydrodynamically when the critical Rayleigh number is determined. However, after the onset of free convection, the temperature profile begins to deviate from its linear one. Thus, the critical time of the onset of free convection can be decided, and the critical Rayleigh number is evaluated by measuring both the thickness of unstable layer and the temperature of the upper surface.

In the present experiments, the characteristics of heat transfer in the melt layer are investigated by varying the depth of melt layer. The detailed procedure is as follows. Distilled and degassed water is injected into the main test chamber and cooled gradually from below until a desired depth of flat ice is obtained. After that, the residual space of the test chamber is filled with water kept at 0°C. Then, the upper wall is heated by the heating element, while the lower wall is cooled by a temperature-controlled ethylen-glycol coolant of constant temperature. Thus, the depth of liquid layer which is precisely measured by microscopic observation through the pair glass installed in the side walls can be varied over a wide range. The rate of heat transfer

is evaluated in a steady state when there is no melting or no freezing advance in the system.

To visualize free convection in the melt layer, thymolblue was used as an indicator and a weak solution of salt was used as the electrolyte.

3. Experimental Results and Discussion

a. Heat flow rate with a temperature variation of upper wall surface T_1

Fig. 4 shows the obtained relation between the temperature of the upper wall surface T_1 and the heat flux through a liquid layer q when the depth of liquid layer H equals 25 mm. From the results, it can be seen that the flux q depends remarkably on T_1. Therefore, it might be understood that the conclusion presented by Yen[5] which the heat flux q is constant regardless of the increased T_1 during melting is not always correct.

Before T_1 reaches 6°C, or thereabouts the q increases monotonically. However, the q corresponding to the T_1 ranging from 6°C to 22°C has a constant value of about 550 cal/m²h, which is a similar value obtained by Yen[5]. However, at $T_1=22$°C the q decreases suddenly and reaches about 450 kcal/m²h at $T_1=23$°C. After that, the q increases proportionally with the increasing T_1. This indicates that the heat transfer mode in the melt layer has changed from convection to conduction in accordance with the critical Rayleigh number $\overline{Ra}$ of about 500 as predicted by the authors.

In Fig. 5, the measured results of temperature distribution in the melt layer are demonstrated using the parameter of T_1. As shown in this figure, there is a constant temperature region suggesting the existence of the convective region in the melt layer near the lower cold wall (0°C). However, the depth of such a convective region gradually reduced with the increasing T_1, and finally the entire liquid layer changes

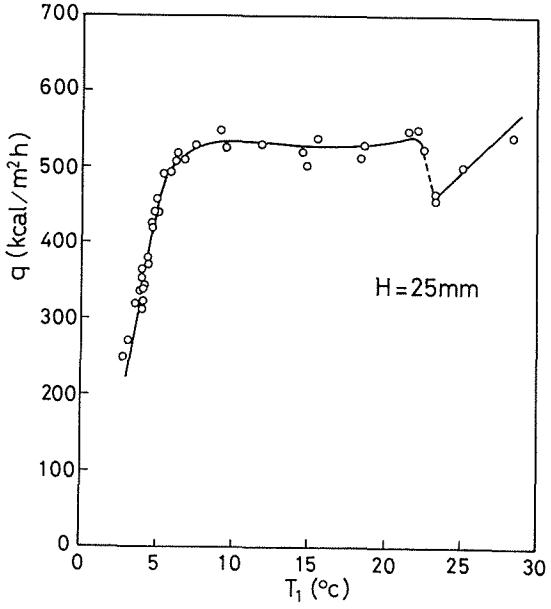


Fig. 4. q vs T_1.

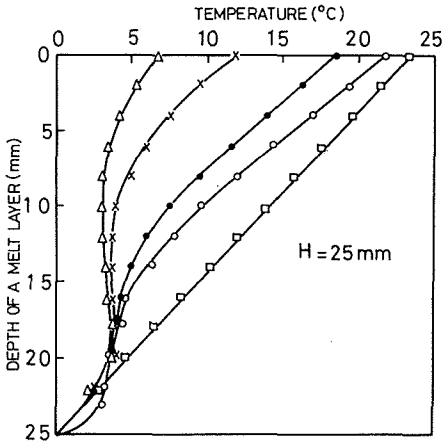


Fig. 5. Temperature distributions in case of $H=25$ mm.

into a sole conductive layer.

b. Evaluation of heat transfer in a melt layer

For the case Fig. 1 (b), the ratio of the depth of convection to that of the melt layer, A, is represented as follows.

$$A=\frac{h}{H}=\frac{T_m-T_2}{T_1-T_2}=\frac{4}{T_1} \quad \text{for } T_1>T_m$$
$$A=1 \quad \text{for } T_1\leqq T_m \tag{1}$$

and Nusselt number Nu and Rayleigh number Ra are defined as

$$Nu=\frac{\alpha H}{\lambda} \tag{2}$$

$$Ra=\frac{g\beta H^3(T_1-T_2)}{\nu\kappa} \tag{3}$$

where $\alpha=q/(T_1-T_2)$, and λ, ν, κ and β are evaluated at $(T_m+T_2)/2$ for $T_1>T_m$, and the arithmetic mean temperature for $T_1\leqq T_m$.

Fig. 6 shows the relation between A and $n=Nu/Nu_s$, where Nu_s proposed by Silveston[7] is evaluated by using the same Rayleigh number as defined by equation (3). In the present results, heat transfer in the melt layer is almost similar to the results by Silveston for the case of $A=1$ ($T_1\leqq 4$°C) where n is nearly equal to unity. However, it should be noted that n becomes gradually smaller with the decreasing A, and the region for $n=1$ exists before $A\simeq 0.7$ ($T_1\simeq 6$°C). Such a unique phenomena can be explained as follows. When a restrictive force exerted on the convective current by the upper rigid wall becomes small with decreasing A, the heat flow in the melt layer increases. This may well correspond to the fact that the region of $n\simeq 1$ still exists in the range of $0.7\leqq A\leqq 1$ in spite of the decreasing convective layer h. Moreover, the entire liquid layer is convective in the above mentioned region, since the water located at the upper part with a temperature higher than 4°C is accompanied by a downward flow of water of 4°C. This phenomenon may be well understood by the visualized view shown in Fig. 7 (a), (b). The black part in the figures shows the convective layer extending adjacently to the upper wall surface in spite of the higher T_1 than 4°C. Virtually, it is recognized that the conclusion proposed by Silveston can be approximately applied for the heat transfer in a melt layer only under the condition of $0.7\leqq A\leqq 1$. However, the value of n decreases monotonically with the decreasing A in the range of $A<0.7$ when a part of convective layer occupying the entire liquid layer decreases.

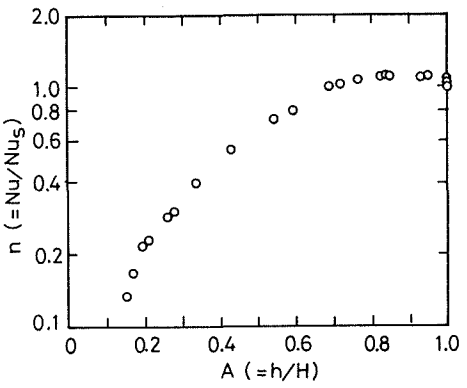
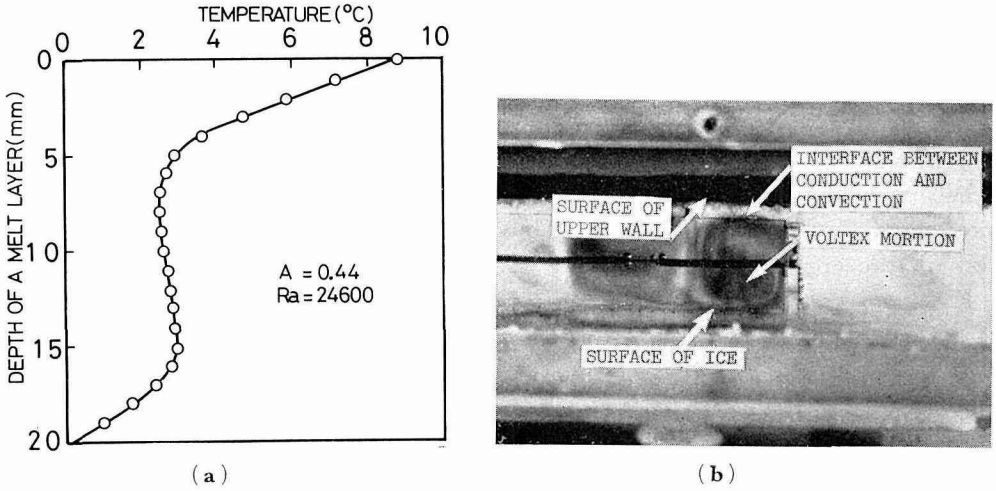


Fig. 6. n vs. A.

The effect of the upper wall on the convection layer vanishes in the range of $A<0.5$, as will be seen in Fig. 7 (a), (b), where the convection layer is situated below



(a) (b)

Fig. 7. Visualized photograph and temperature distribution.

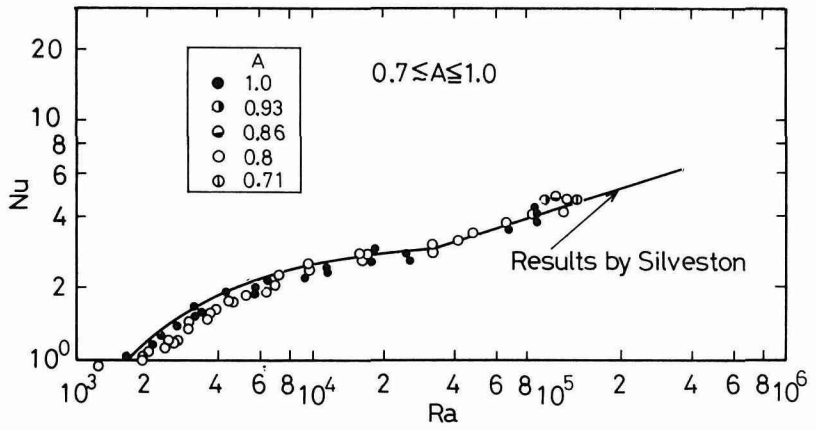


Fig. 8. Nu vs. Ra in case of $0.7<A\leqq 1.0$.

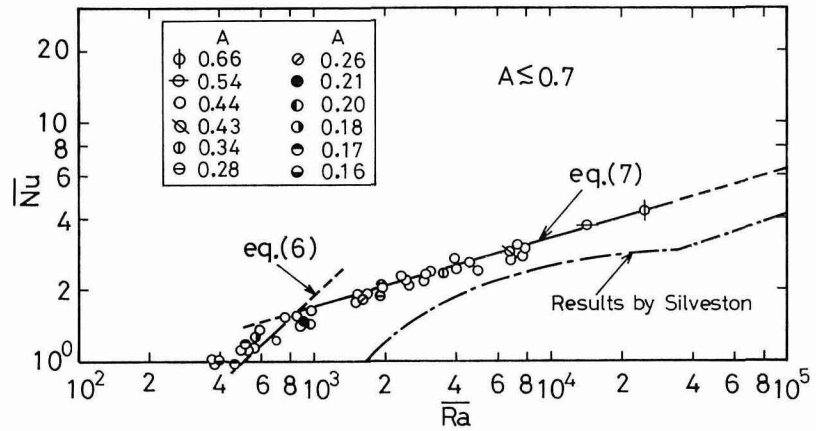


Fig. 9. $\overline{Nu}$ vs. $\overline{Ra}$ in case of $A<0.7$.

the conduction layer. Therefore, the heat flux q for $A<0.5$ ($T_1>8°C$) is almost constant in spite of the increasing T_1.

Fig. 8 shows the experimental results given by the equation (2), (3) for the case of $0.7<A<1$. The results are in good agreement with the results by Silveston[7] which are indicated by using a solid line. Therefore, it is clear that the results by Silveston can be approximately applied for the heat transfer in the melt layer under the restricted conditions mentioned above. However a small deviation between both results is seen in the creeping region.

Fig. 9 shows the results for $A<0.7$. Nusselt and Rayleigh numbers are defined as

$$\overline{Nu}=\frac{\alpha h}{\lambda} \qquad (4), \qquad \overline{Ra}=\frac{g\beta h^3(T_m-T_1)}{\nu\kappa} \qquad (5)$$

respectively, where $\alpha=q/(T_m-T_2)$, ν, κ, λ and β are evaluated at $(T_m+T_2)/2$. From Fig. 9, it may be seen that heat transfer in a melt layer depending on A could categorically be evaluated by the following two expressions in the range of $A<0.7$.

$$\overline{Nu}=0.0037\,\overline{Ra}^{0.9} \qquad 500<\overline{Ra}<900 \qquad (6)$$

$$\overline{Nu}=0.24\,\overline{Ra}^{0.28} \qquad 900<\overline{Ra}<30000 \qquad (7)$$

c. A consideration of the onset of free convection in melt layer

Fig. 10 shows the obtained data indicating the relation between the temperature of upper wall T_1 and the critical Rayleigh number $\overline{Ra}_c$, which represents the criterion of the onset of free convection, along with the results by Sun *et al.*[8] and Katto *et al.*[9]

Figs. 11, 12 and 13 show examples of temperature distribution in the melt layer before and after the onset of free convection. From these figures, it is clearly shown that the linear profile changes into a curved profile in accordance with the variation

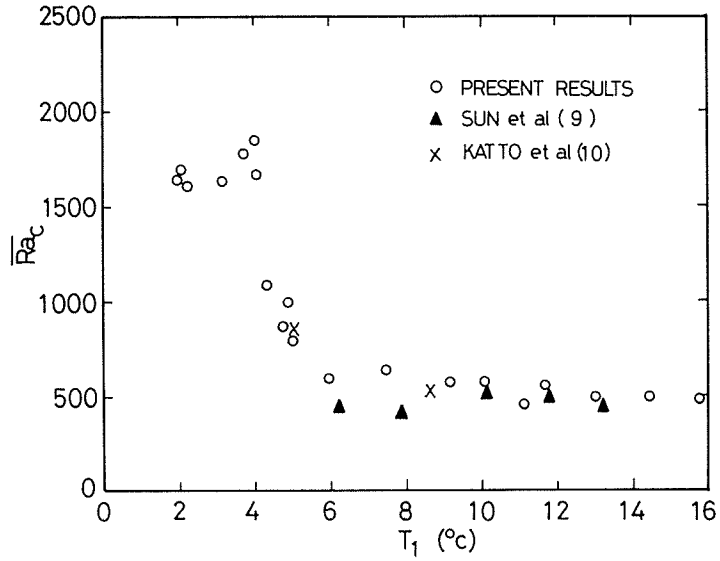


Fig. 10. Critical Rayleigh number.

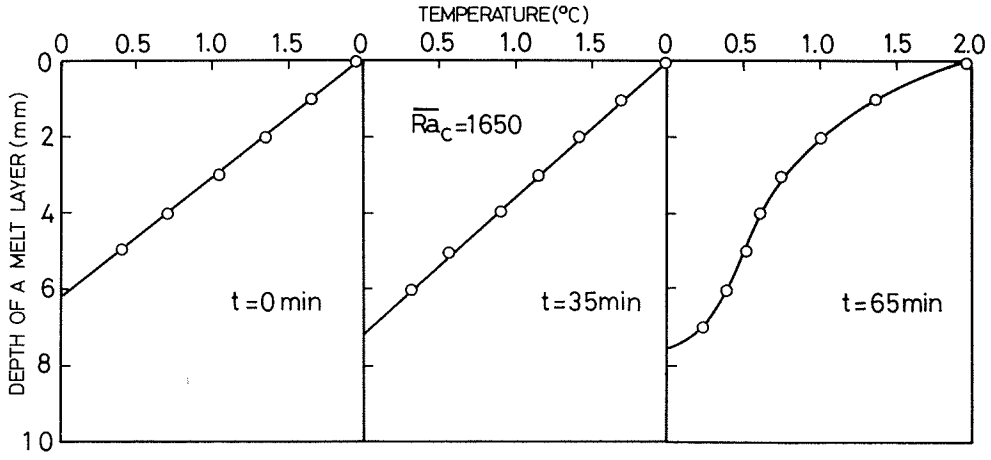


Fig. 11. Temperature distributions in case of T_1=2°C.

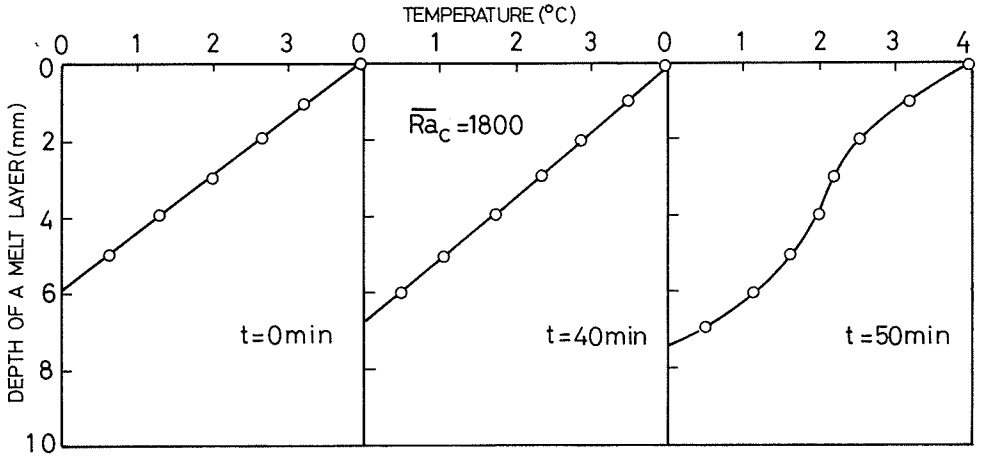


Fig. 12. Temperature distributions in case of T_1=4°C.

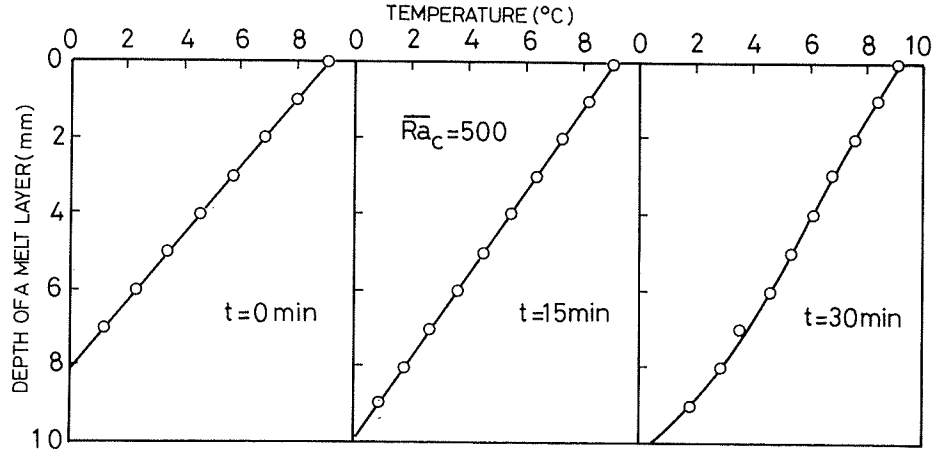


Fig. 13. Temperature distributions in case of T_1=9°C.

of conduction to convection. In Fig. 10, it can be recognized that $\overline{Ra}_c$ is nearly equal to 1700, which is the same value as given by Silveston[7] in a range of $T_1 \leqq 4°C$. On the other hand, $\overline{Ra}_c$ suddenly decreases in the range of $T_1 > 4°C$, because the restrictive force exerted on the free convective motion becomes small with the increasing T_1, while $\overline{Ra}_c$ becomes a constant value of about 500 for $T_1 > 8°C$.

4. Conclusions

The conclusions for the experimental results of convective heat transfer in a melt layer of ice heated at its upper bounding surface are as follows.

1. Heat flux q through a melt layer depends remarkably on the temperature of the upper surface T_1, but there is a region having a constant value of q regardless of the increased T_1.

2. The ratio of the depth of convection layer to that of the entire melt layer, A, is a useful parameter for the evaluation of the heat transfer in a melt layer. The experimental results by[7] Silveston are valid for the prediction of the heat transfer in the range of $0.7 < A$, while the following expermental equations are valid in the range of $A < 0.7$.

$$\overline{Nu} = 0.0037\,\overline{Ra}^{0.9} \qquad 500 < \overline{Ra} < 900$$

$$\overline{Nu} = 0.24\,\overline{Ra}^{0.28} \qquad 900 < \overline{Ra} < 30000$$

3. Experimental considerations are given to the onset of free convection and it is concluded that the critical Rayleigh number $\overline{Ra}_c$ varies from 1700 to 500 with the increasing temperature of upper wall surface.

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