EXPERIMENTAL INVESTIGATION OF NATURAL CONVECTION FROM A HORIZONTAL ICE SURFACE MELTING IN PURE WATER

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A study on natural convection from a horizontal ice surface melting in pure water was conducted experimentally for the ambient water temperature from 2℃ to 10℃. Natural convection flow around upward- or downward-facing horizontal ice plate was divided into three regions according to the temperature variation of ambient water. The flow patterns of three regions were no flow, two-dimensional steady laminar flow and unsteady flow. Mean Nusselt number for the upward-facing surface had its maximum value at about 3℃ of ambient water temperature. However, in the case of the downward-facing surface it increased as the ambient water temperature increased.

Key Words: Natural Convection, Upward-facing Horizontal Surface, Downward-facing Horizontal Surface

1. INTRODUCTION

Although natural convection flows near a horizontal surface in an infinite fluid medium has been studied extensively for several decades, they have received less attention than natural convection near vertical surfaces. But natural convection near a horizontal surface is important in industrial application.

Natural convection due to a finite, isothermal plate has been studied theoretically by Clifton and Chapman(1969). They solved governing equations using the conditions that the boundary layer depth at edges is equal to the critical one. Aihara et al(1972) carried out an experiment on a heated horizontal plate at Rayleigh number of the order of 10^7 for air. The validity of Gill et al's(1965) theoretical conclusion that the similarity solutions could not be obtained for free convection along a downward-facing, isothermal, heated surface was confirmed by experiment. Pera and Gebhart (1973) studied the effect of a small surface inclination on flow and transport by considering the perturbation of flow over a horizontal surface. They studied the nature of laminar boundary-layer using a Mach-Zehnder interferometer. Forbes and Cooper(1975) obtained numerical solutions for a horizontal layer of water cooled from above to near freezing. They reported that 4℃ isothermal line divided the depth of water into a region of hydrodynamic instability below the isotherm and a stable region of water above it. Yousef et al(1982) measured the local and the average heat transfer coefficient for upward-facing isothermal horizontal surfaces using a Mach-Zehender interferometer. They observed that periodical flow instabilities caused random changes up to 23 percent of mean values in the average Nusselt number. Joshi and Gebhart(1983) have made measurements about the flow generated above a heated line source in cold water around the extremum point. They visualized that very complex flow patterns existed around density extremum temperature, due to the bidirectional buoyancy force. Schulenberg(1985) determined analytically the laminar steady state convections below a horizontal infinite strip and below a horizontal circular plate, and by appling method of matched asymptotic expansions, he obtained local similarity solutions for the limiting case of high Prandtl numbers. Recently, Myamoto et al(1985) analyzed numerically the free convection around vertical and horizontal short plates. They obtained the relations between Nusselt and Grashof numbers with an error within 6 percent. Kim et al(1990) studied theoretically natural convection from a horizontal isothermal surface immersed in water near its density extremum. In each case of upward- or downward-facing surface, they showed steady two dimensional flow regimes and no solution region according to the variation of ambient water temperature.

Given the previous studies discussed above, most of the studies on natural convection near horizontal plate have been performed for air. Actually the free convection problems in cold water arise very frequently in natural environment and industry, and yet more detailed informations of them are needed.

The present study deals with experiments concerning natural convection flow around upward- or downward-facing surface of a horizontal ice plate. The theoretical results(Kim et al,1990) are compared with those of experiments.

2. EXPERIMENTS

In this experiment, an ice slab 18.4cm wide, 23.2cm long and initially 3cm thick was used. The ice was surrounded by expanded polystyren insulation of thickness 2.5cm supported by an acrylic plastic "picture frame"(see Fig. 1). To reduce the effects of disturbance at leading edge of the ice, two

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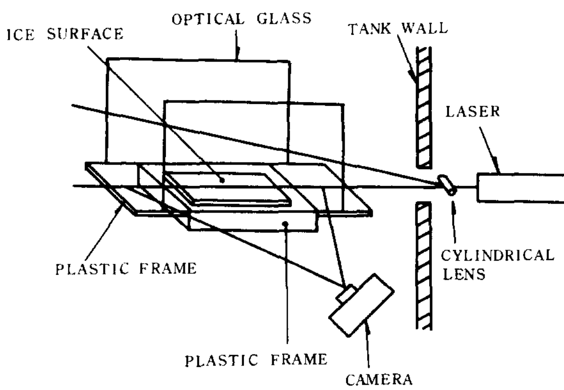


Fig. 1 Schematic diagram of the test set up

acrylic plastic plate 25cm wide, 30cm long and 1cm thick was attached to the left and right sides of the plastic frame. In order to confirm two directional flow, two optical glasses, 30cm high, 60cm long and 3mm thick were fixed at front and back side of the plastic frame. By these glasses, cross flows entered from front and back side were prevented, and it was certified that there was no cross velocity component in visualization photographs.

After freezing the ice slab, the mold was removed from the freezer, and it was allowed to warm up slowly until the ice reaches the equilibrium temperature of 0℃. The ice slab.was immersed into the tank, and flow around the surface of ice slab was visualized. The ice slab was melted in water filled in a glass tank 150cm deep, 150cm long and 100cm wide. The glass tank was filled to a depth of 140cm with distilled water. To visualize the flow, 0.85g of pliolite ground to 40μm size was added to the water. Pliolite is a solid white resin manufactured by Goodyear Chamical Compay. Pliolite is virtually insoluble in water and has a specific gravity of 1.026. The 40μm particles remain suspended in water indefinitely.

The plane slit beam of a 15mW helium-neon laser was flashed on a vertical or horizontal plane around horizontal ice plate. The plane slit beam was made by a cylindrical lens whcih spreads the beam in one direction. Side scattering of the laser light at the pliolite particles made them visible.

Twelve 0.25mm copper constantan thermocouples were installed to obtain the vertical and horizontal temperature gradient in the ambient water. The laser beam was aligned perpendicular or parallel to the ice surface to take pictures of vertical or horizontal plane. The particles in the laser beam could be seen through the glass walls of the tank. The ice slab was allowed to melt for approximately 10 minutes after the immersion to permit transient effect to die out. Time exposure photographs of the flow were then taken using a moter-driven 35mm Cannon camera controlled by a microprocessor and a solenoid valve. Sequential photographs of the flow were taken by using a microprocessor. Various time exposures were controlled by the programming.

An experiment was run for an ice slab, initially at 0℃ throughout, immersed in water at a preset temperature. After finishing the experiment, the ice slab was removed from the water tank, and then it was carried to a cold room. The mean melting depth, obtained from the local melting depth, was converted to a melting weight, and melting rate, m, was determined by dividing it with total immersed time of the ice slab in ambient water. Knowing the melting rate of ice, m, at a particular water temperature, the Nusselt number can be determined by using the latent heat of fusion h_u=79.77cal/g, and taking into account the area of the ice slab. We assume that the conduction of heat into the ice slab is negligible. The mean Nusselt number is evaluated as :

$$Nu=\frac{hL}{k}=\frac{mh_u}{wk(T_\infty-T_w)} \quad (1)$$

Where L(=23.2cm) is the length of the ice surface, h is the average heat transfer coefficient, w(=18.4cm) is the width of ice, T_∞ is ambient water temperature, and T_w is temperature of ice slab. Thermal conductivity, k, is evaluated at the film temperature as :

$$T_f=(T_\infty+T_w)/2$$

3. RESULTS AND DISCUSSION

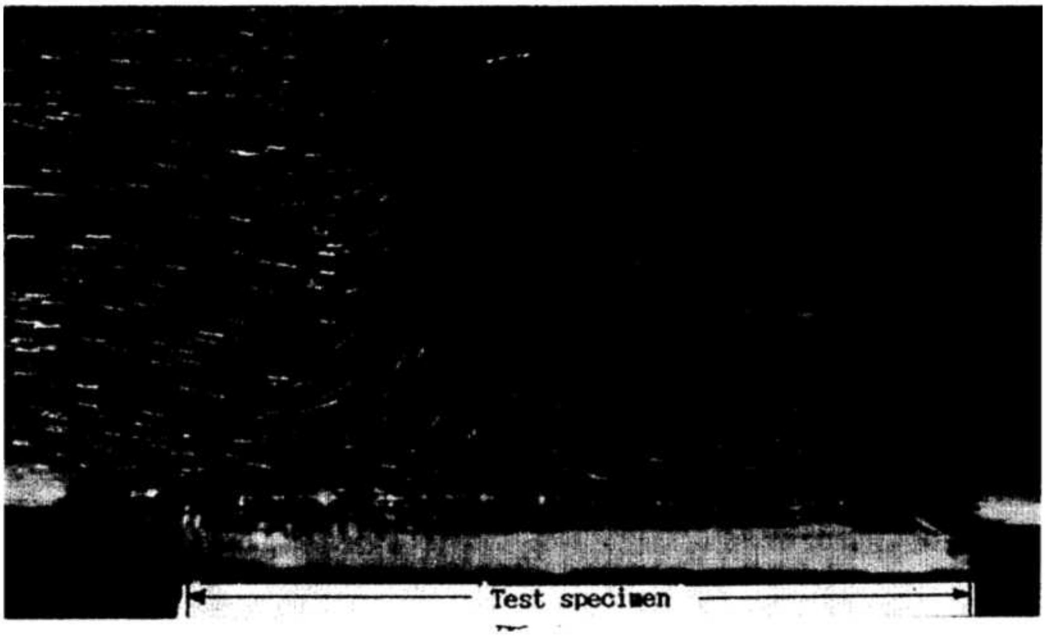
3.1 Flow Patterns

In each visualization photographs, streaks are made by the particles of pliolite. And at the both sides of the ice surface the white line is made by the insulation plates attached to picture frame. The ice toward the camera has a bright, mottled appearance which results from the light striking the ice surface. The light penetrates the ice and is, in part, scattered by air bubbles trapped deep below the surface of the ice. The location of the ice surface was indicated typically in the visualization photograph of Fig.2(a).

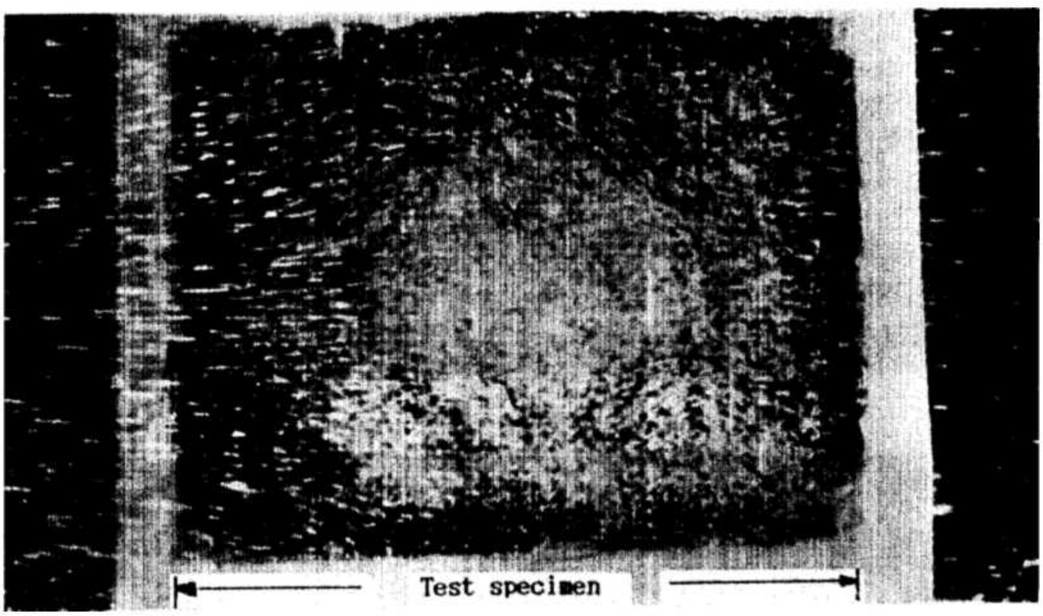
Figure 2(a) shows the visualization photograph taken for the vertical flow field adjacent to upward-facing surface of a horizonal ice slab immersed in ambient water at T_∞=2℃, Symmetric upward flows arise at the region near the centerline of the ice surface as the density of water near the ice surface is smaller than that at the outside of thermal boundary layer. The fluid above the edges of the ice slab flows parallel to the surface, toward symmetric axis line, in order to make up for the deficient mass caused by upward flow. As it approaches to the center line of the ice surface, its direction of flow changes to downward, next to upward, and finally the flows near the center line make a plume. The downward flow very close to the ice surface becomes more vigorous in order to satisfy the continuity of flow for plume.

Figure 2(b) shows visualization photograph taken for the horizontal flow field parallel to and 2cm high above the horizontal ice surface immersed in ambient water at 2℃. There is no streak in the white part of the photograph due to the white color of the plastic frame. In the Fig. 2(b), it is shown that the fluid flows parallel to the ice surface, toward symmetric centerline, from the edges of the ice slab. Having only horizontal component of velocity at the region of the plume, the pattern of flow looks like a spot at the region near the symmetric centerline. From the facts observed above, it can be confirmed that the flow in the velocity field is two-dimensional. The similar flow patterns can be observed in the ambient water temperature of 2℃ ≤ T_∞ < 4.5℃.

Figures 3(a)~3(d) show sequential visualization photograph taken with 20sec interval for the vertical flow adjacent to upward-facing surface of a horizontal ice slab immersed in ambient water at T_∞=4.5℃. In the case that temperature of the ambient water is higher than 4.4℃, the flow patterns become quite different from that of the foregoing cases. Several vortices appear in the flow field at T_∞=4.5℃ as



(a) vertical plane at the centerline of the ice surface



(b) horizontal plane 2cm above from the ice surface

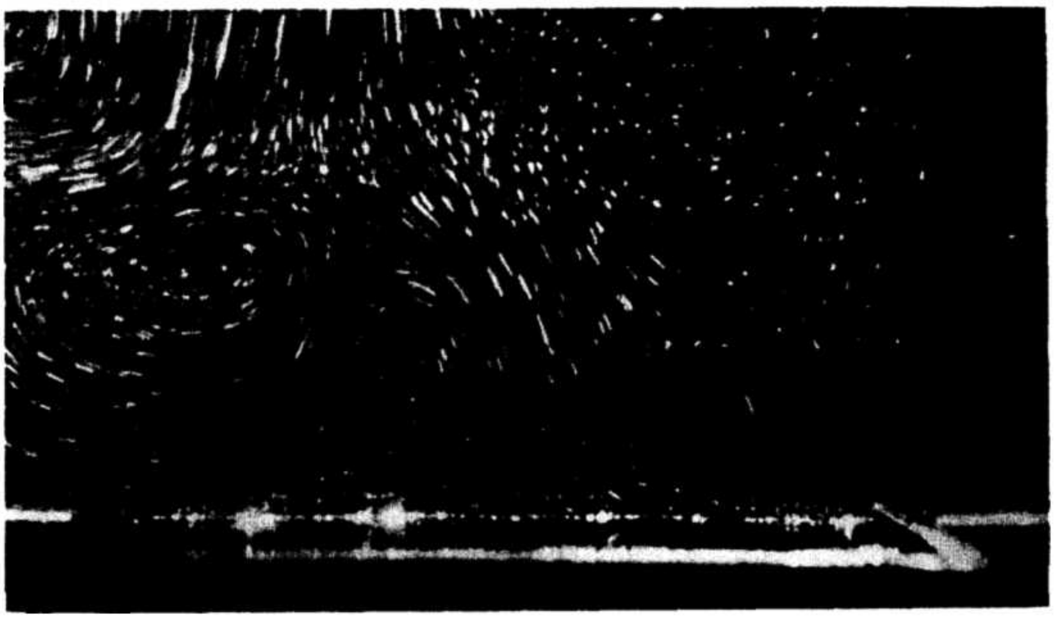
Fig. 2 Flow adjacent to an upward-facing horizontal ice surface at $T_\infty = 2^\circ C$

shown in Fig. 3(a). Flows are unsteady, and the shapes and the locations of the vortices are being altered with time. At this temperature, the light water near the symmetric line is heated and becomes more dense in the course of rising upward. The density of water around the outer edge of thermal boundary layer has maximum value. With these conditions the upward plume near the centerline is weaker than that in the range of $2^\circ C \le T_\infty \le 4.4^\circ C$. As this upward plume reaches the outer edge of thermal boundary layer, water becomes sufficiently warm through mixing and diffusion, thus the buoyancy force becomes negative, and the upward plume then decelerates and finally changes its direction. This produces vortices. At 20 sec later, the previous vortices become a little small and move to upward and right or left direction as shown in Fig. 3(b). Then, these vortices become more weak in the whole flow fields(Fig. 3(c)). As time goes by, new strong vortices reappear near the edge of the ice surface as shown in Fig. 3(d). These flow patterns are repeated with the lapse of time, and the period is changed at each time step. This phenomenon arises up to the vicinity of $T_\infty = 6^\circ C$.

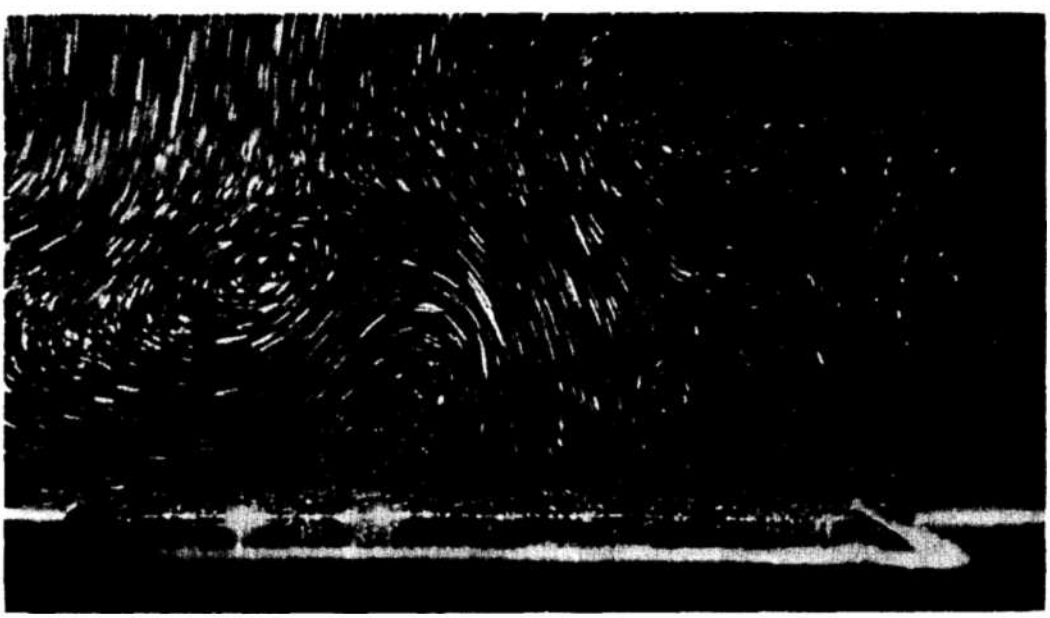
As the ambient water temperature increases, the vortices become smaller and affects narrower region near the ice surface. And the vortex disappears at upper part of the flow field as shown in Fig. 4(a). Fig. 4(b) shows a photograph 100 sec later than Fig. 4(a). In the whole flow fields, the flow patterns are similar, but the locations of the vortices near the ice surface and the shapes of the streaks are changed with time.

At $T_\infty=7$ ℃, the portion of water in the thermal boundary layer, whose density is small than that in the ambient water, is very small. Thus the upward flows arise only in the narrow layer close to the ice surface, and the greater part of the ambient water adjacent to the horizontal ice surface is stationary as shown in Fig. 5. As the ambient water temperature increases above this temperature, the whole flow fields are stationary.

Figure 6 shows visualization photograph taken for the vertical flow field adjacent to the downward-facing surface of a horizontal ice slab. Since the density of water in the thermal boundary layer is mostly smaller than that in the ambient water of the range of $T_\infty<4.4$℃, there occurs no flow. As the temperature of ambient water increases, weak downward flows begin to arise from both edges of ice as shown in Fig. 7(a). Fig. 7(b) shows a photograph taken 20 sec later. These photographs show that the flow is changed with time. Thus, it is considered that this ambient water temperature is a starting point of unstead down flow. Figure 8(a) shows more vigorous flows than previous photographs as the ambient water temperature increases. Figure 8(b) taken 60



(a)



(b)

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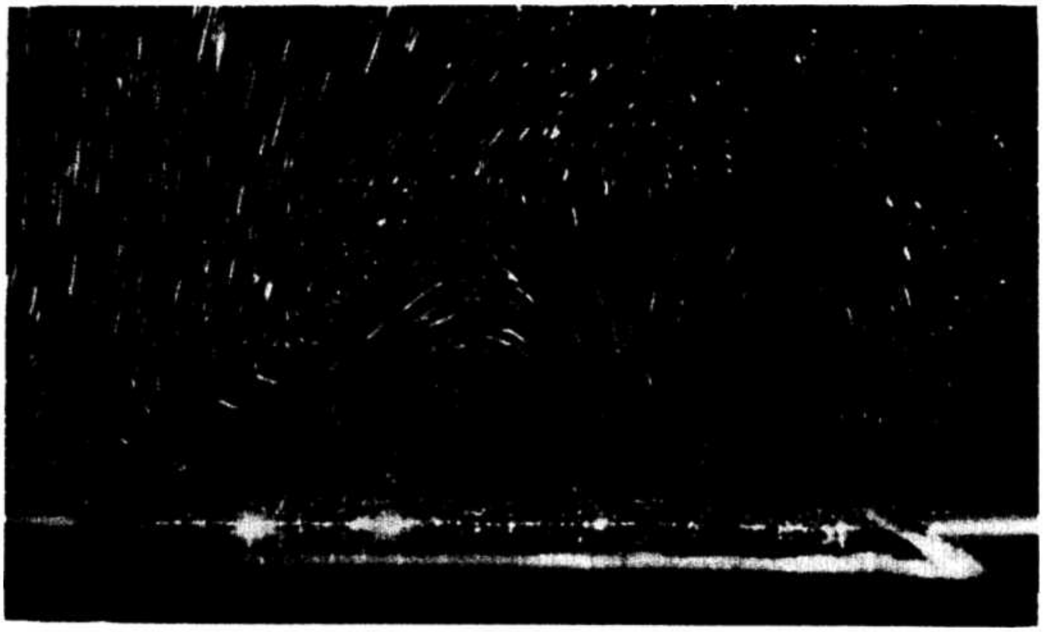
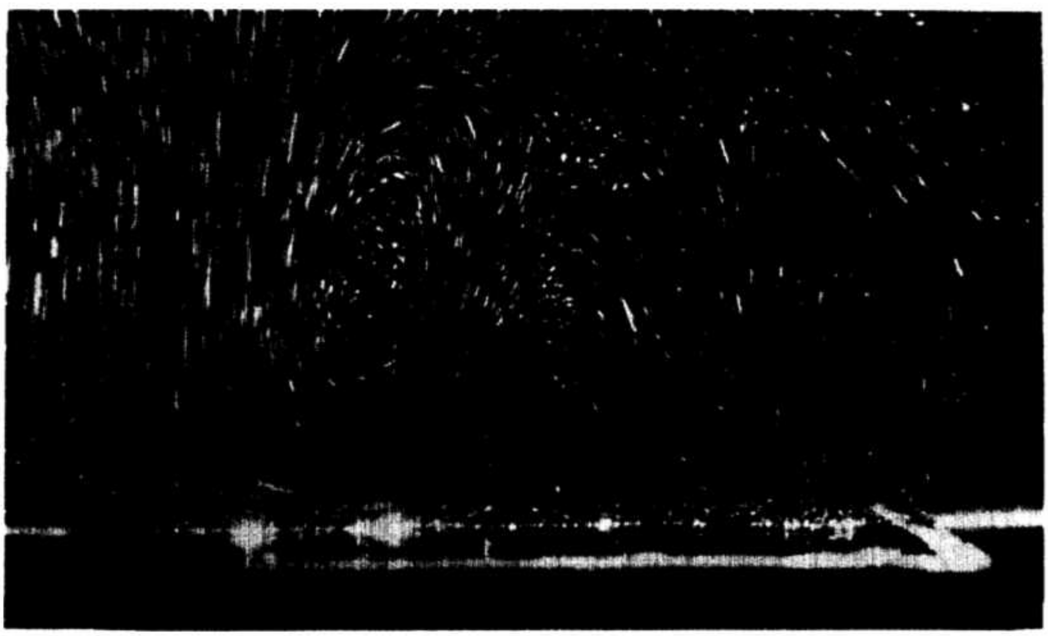


(c)



(d)

Fig. 3 Flow adjacent to an upward-facing horizontal ice surface at $T_\infty=4.5$℃ ; (a) ~ (d) are sequential photographs taken with 20sec interval

sec later shows that the flow field are extended near the ice surface and close to the centerline of the ice specimen. Similar flow patterns appear in the range of $4.4\leq T_\infty<4.9$℃.

As the temperature of ambient water increases above this temperature, the flow forms a plume below the centerline of the ice surface as shown in Fig. 9 and 10. And this flow pattern remains unchanged with time. In this symmetric flow field, the fluid below the edges of the ice surface has the upward component of velocity. And it turns its direction to downward near the axis of symmetry to form a plume. This flow occurs more vigourously than in the case of upward-facing ice surface. As the temperature of ambient water increases, the flow becomes more vigourous.

3.2 Mean Nusselt Number

The local heat transfer coefficient, h_x, average heat transfer coefficient, h, and average Nusselt number, Nu, can be defined as :

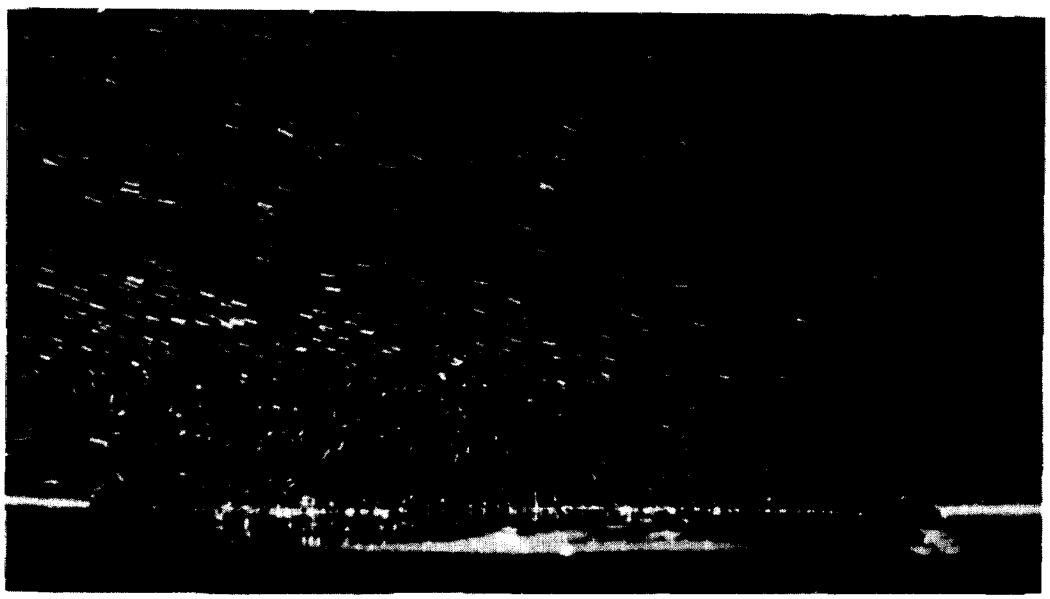
$$hx = -\frac{k}{T_x - T_\infty}\frac{\partial T}{\partial y}\bigg|_{y=0} \tag{2}$$

$$h = \frac{1}{L}\int_0^L h_x \, d_x \tag{3}$$

$$Nu = \frac{hL}{k} \tag{4}$$

Where x, y, k, T_w and L represent horizontal coordinate, vertical coordinate, thermal conductivity, ice surface temperature, and length of the specimen respectively.

Figure 11 shows numerically calculated average Nusselt numbers (Kim et al, 1990) and present experimental results. The average Nusselt number of the upward-facing surface of the specimen has its maximum value at about 3℃. As the temperature decreases from 3℃ to 0.5℃ or increases to 4.4℃,



(a)

(b)

Fig. 4 Flow adjacent to an upward-facing horizontal ice surface at $T_\infty = 6$℃ ; (a) and (b) are taken with 100sec interval the average Nusselt number decreases. The experiment, however, has been performed within the range from 2℃ to 10℃. The experimental values for the region of unsteady or stagnation, where the calculated results could not be obtained, decrease as the temperature increases. When flows are weaker, the average Nusselt number is smaller for the whole temperature range. The average Nusselt number at the downward surface of the specimen increases as the temperature increases, because the flows become vigorous as the temperature of ambient water increases. The average Nusselt numbers of unsteady or stagnant regions decrease as the temperature of ambient water decreases in the case of downward-facing surface too. Since there is no flow in the stagnant region, heat is transferred only by conduction. There is some discrepancy between numerical and experimental results due to the measuring errors of local melting depth, the errors involved in numerical scheme and round off error. But the maximum discrepancy is less than 10 percent.

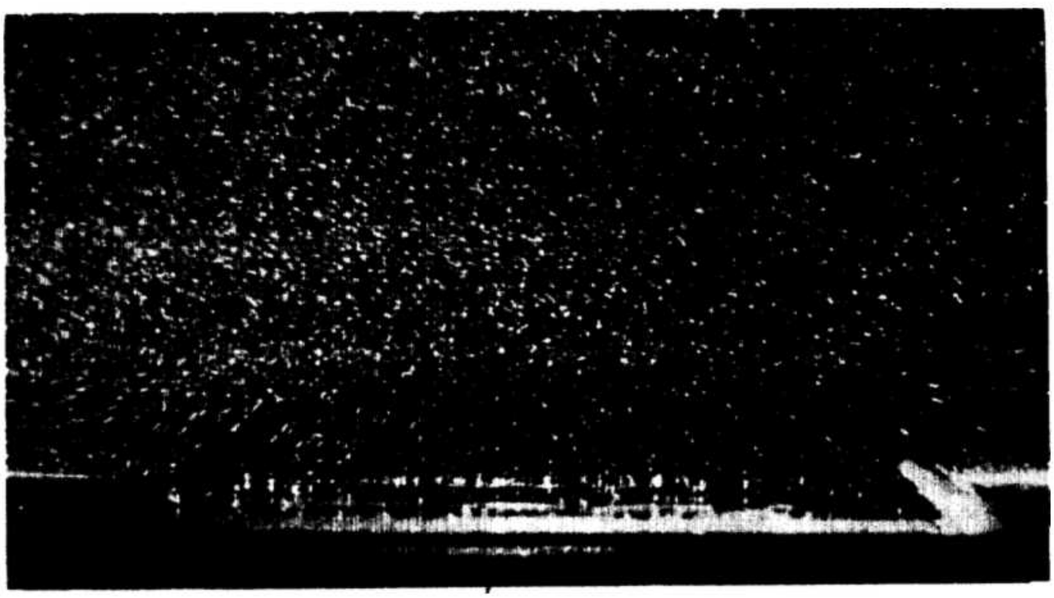


Fig. 5 Flow adjacent to an upward-facing horizontal ice surface at $T_\infty = 7$℃

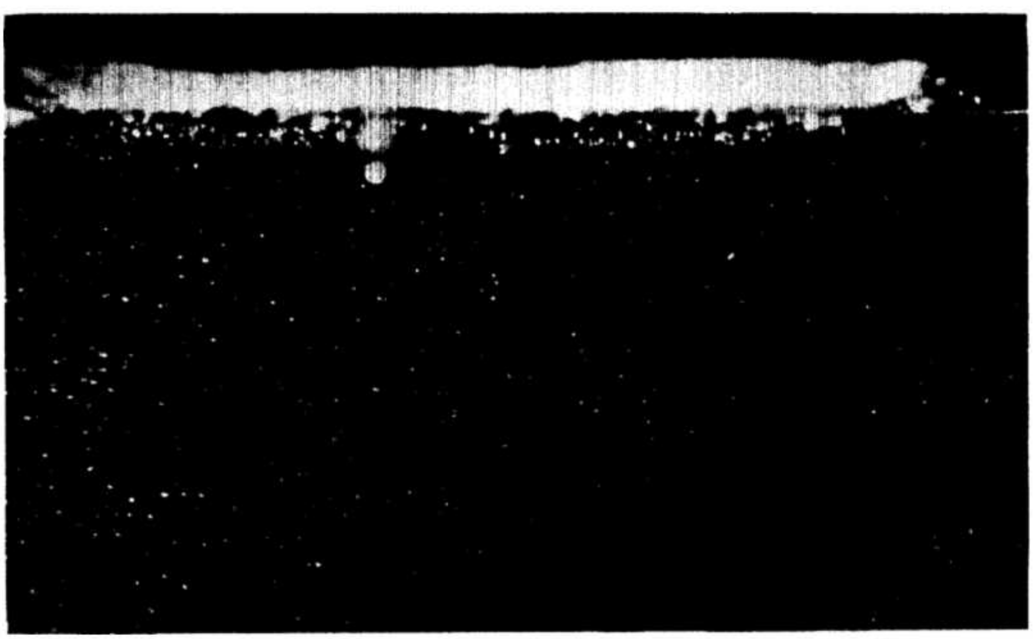
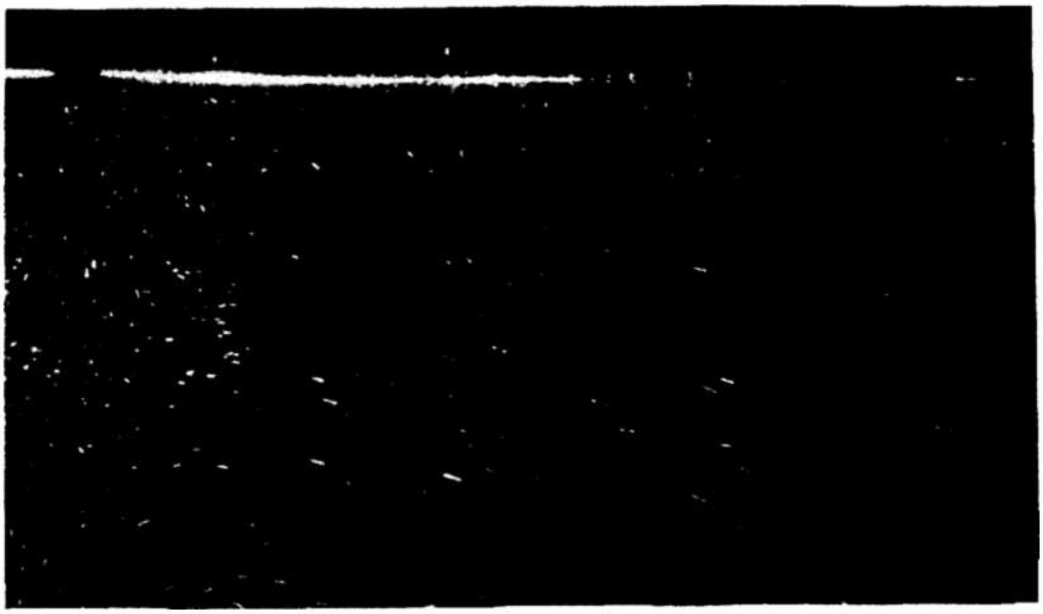
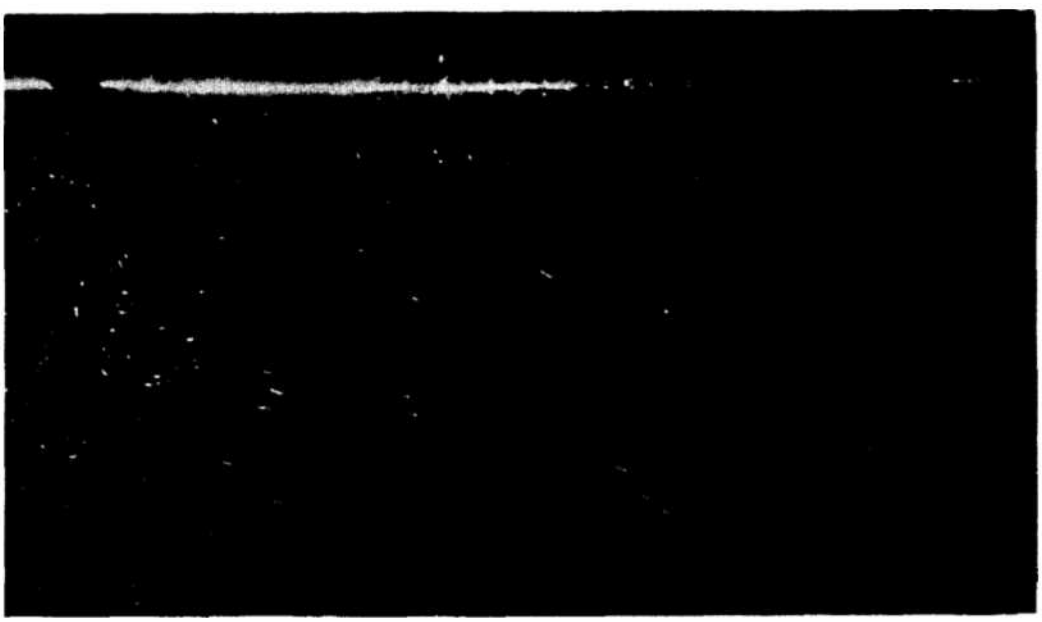


Fig. 6 Flow adjacent to an downward-facing horizontal ice surface at $T_\infty = 4$℃



(a)



(b)

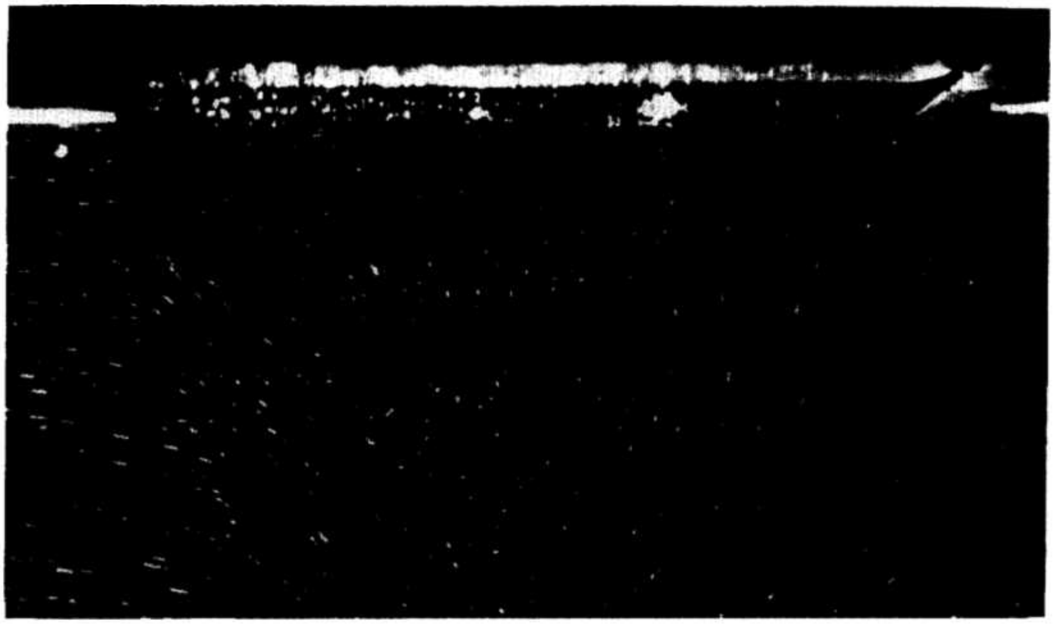
Fig. 7 Flow adjacent to a downward-facing horizontal ice surface at $T_\infty=4.4$℃ ; (a) and (b) are taken with 20sec interval

Therefore it is considered that the expegimental and numerical values are quantitatively in good agreement. The average Nusselt number has smaller values than those of the vertical ice surface obtained by Riu(1984) for the whole temperature range.

The present experiment was restricted to natural convective flows around the ice specimen having finite dimension. Thus, the limits of characteristic length of the ice surface showing similar flow patterns are a subject to be studied.

4. CONCLUSIONS

Experimental results presented here document the nature of the natural convection flow adjacent to the upward- and



(a)

(b)

Fig. 8 Flow adjacent to an downward-facing horizontal ice surface at $T_\infty=4.7$℃ ; (a) and (b) are taken with 60sec interval

downward-facing surfaces of a horizontal ice surface melting in pure water at ambient water temperature between 2℃ and 10℃.

In the case of upward-facing surface of a horizontal ice surface, there are two-dimensional laminar flows of steady state in the range of ambient water temperature, 2℃ $\leq T_\infty <$ 4.4℃. Near the edges of the ice surface, the fluid flows parallel to the ice surface, toward the axis of symmetry. And as it approaches to the symmetric axis of the ice surface, its direction of flow changes to downward, next to upward, and finally the flows at symmetric axis makes a plume. The thickness of plume is thinnest when the ambient water temperature is about 3℃ where the flow is most vigorous. Vortices changing with time are formed in the range of

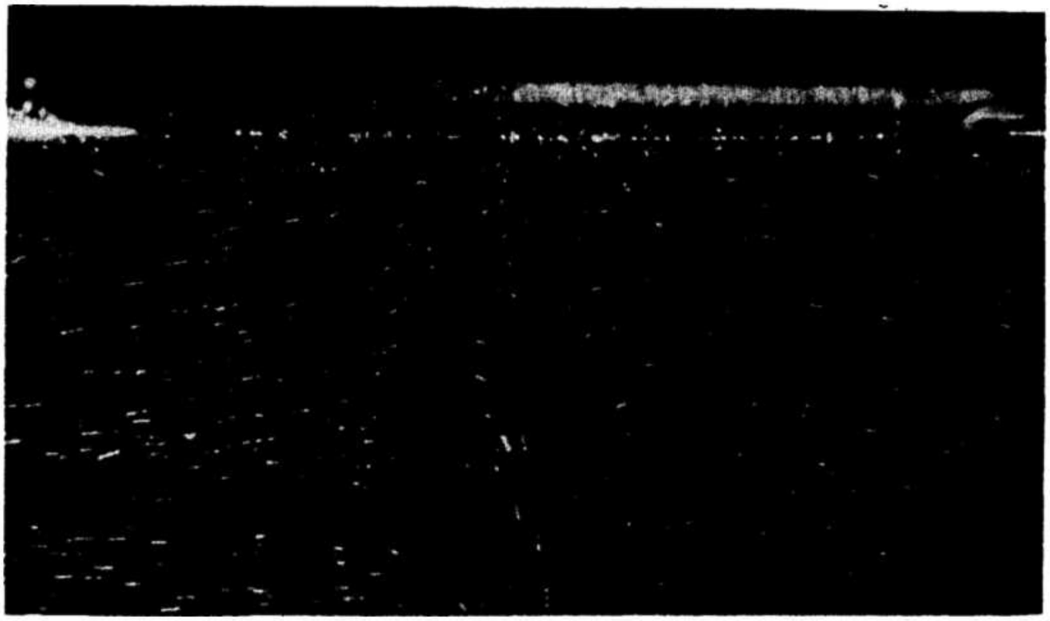


Fig. 9 Flow adjacent to an downward-facing horizontal ice surface at $T_\infty=4.9$℃

Fig. 10 Flow adjacent to an downward-facing horizontal ice surface at $T_\infty=6$℃

ambient water temperature, 4.5℃ ≤ T_∞7.0℃. When the ambient water temperature is above 7℃, the water near the ice surface becomes stationary and heat is transferred only by conduction.

In the case of downward-facing surface of a horizontal ice surface, there are no flows in the range of ambient water temperature, $T_\infty<4.4$℃. Very weak down-ward flows changing with time arise in the range of 4.4℃ ≤ $T_\infty<4.9$℃, and steady state laminar flows form in the range of 4.9℃ ≤ T_∞. The laminar flow pattern is similar to the case of upward-facing surface except the fact that upwad component of velcoity is large at both sides of the plume.

The mean Nusselt number for the upward-facing surface has its maximum value at about $T_\infty=3$℃. However, in the

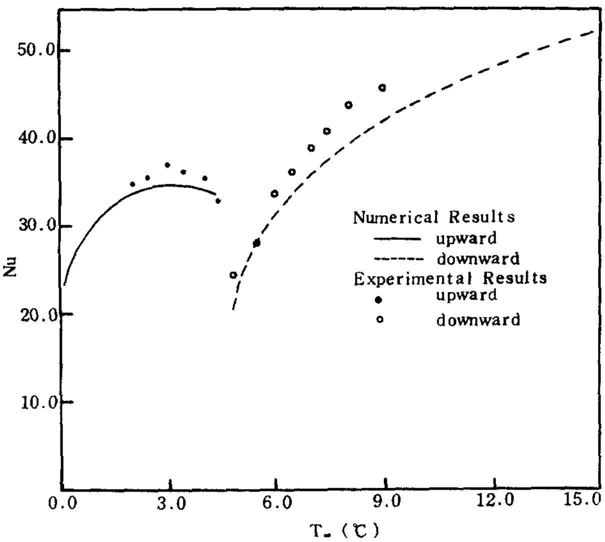


Fig. 11 Comparision of the mean Nusselt numbers between numerical and experiemental results

case of the downward-facing surface it increases as the ambient water temperature increases.

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