Title	Freezing Behavior of Layered Air-Liquid Flow in a Circular Tube
Author(s)	Fukusako, Shoichiro; Takahashi, Masato
Citation	北海道大學工學部研究報告, 133, 27-38
Issue Date	1986-10-31
Doc URL	https://hdl.handle.net/2115/42013
Type	departmental bulletin paper
File Information	133_27-38.pdf

北海道大学工学部研究報告
第133号（昭和61年）

Bulletin of the Faculty of Engineering.
Hokkaido University, No. 133 (1986)

Freezing Behavior of Layered Air-Liquid Flow in a Circular Tube

Shoichiro FUKUSAKO and Masato TAKAHASHI

(Received June 30, 1986)

Abstract

This paper describes the experimental results of transient freezing characteristics of layered air-water flow in a circular tube, in which cooled air and water flow together. The experiments were carried out under a variety of conditions of air velocity, water velocity, and tube-wall temperature kept uniform less than freezing temperature of water. Special attention was paid on photographical visual observations of the developing ice layer along the tube wall. It was shown that the water level rose based on the growth of ice along the tube wall which was submerged in the water flow then the ice layer along the upper tube wall grew thicker than lower position due to the splashing of the water droplets based on an intense ripple which occurred at an air-water interface.

1. Introduction

In cold regions, freezing phenomena of water are generally observed, such as the freezing of rivers, lakes, and water pipes. Technologically, the phenomena are efficiently utilized in the fields of ice manufacture, frozen food, freeze-drying, and desalting of sea water. However, the freezing often causes the fractures of a power-plant pipes, heat exchangers etc..

For that reason, a number of studies$^{(1)-(7)}$ have been performed to investigate the freezing characteristics of flows between horizontal parallel plates and in a return bend, and it seems that the conclusive results of the characteristics of a single phase flow may be obtained. On the other hand, in the case of a large scale pipe-line or a drain pipe, in which the air phase and liquid phase usually coexist, little is know about the freezing characteristics of layered air-water flow in a circular tube.

In this paper, an experimental study has been performed to investigate the transient freezing behavior of layered air-water flow in a circular tube, in which the cooled air and the water flow together. The experiments were carried out under a variety of conditions of air velocity, water velocity, and tube-wall temperature. Photographical visual observations of the developing ice layer along the tube wall were extensively performed.

Nomenclature

T_w : tube-wall temperature
H : water level
L : axial distance from inlet of test section
r_0 : inner radius of test section
r : distance from center of test section to surface of ice layer
u_a : air velocity at inlet of test section
u_w : water velocity at inlet of test section
t : time
t_c : time of onset of freeze-off
ϕ : counter-clockwise degree from top of tube wall

2. Experimental Apparatus and Procedures

2.1 Experimental Apparatus

The schematic diagram of the present apparatus is presented in Fig.1. The main parts of the experimental apparatus consist of a test section, a water-flow loop, a cooled air-flow loop, and a coolant-flow loop. The test section was a concentric tube of 1000mm in length. The inner tube was a plexiglass cylinder, the outer diameter of which was 68mm and the inner one was 65mm. The outer tube was a lucite-tube with an outer diameter of 135mm and an inner one of 125mm. Transparent ethylen-glycol($HOCH_2CH_2OH$, density 1117kg/m^3) was used as the coolant to observe the freezing characteristics in the tube.

In order to obtain uniform temperature of tube wall, temperature-controlled brine was circumferentially injected along the tube wall from five nozzles which were arranged at the same intervals through the outer tube wall. To measure temperatures of the tube wall, the air flow, and the water flow, six copper-constantan thermocouples of 0.1mm in diameter were axially installed at the tube wall and two additional thermocouples at the inlet and the outlet of the test section were set respectively. The weir was located at a distance of 80mm from outlet of the test section, and the water level was successfully controlled by adjusting the weir height. In the water-flow loop, a heat exchanger and a heater for controlling the water temperature were installed in the storage tanks which were connected to the inlet and outlet of the test section, respectively. The main water was circulated by a centrifugal pump (0.75kw, 1470r.p.m) through a vinyl chloride pipe (65mm ID), whose flow rate was controlled by the cotrolling valves and whose discharge was measured by a calibrated orifice meter.

In the system of the cooled air-flow loop, a low temperature wind tunnel (the maximum velocity: 28m/s, the maximum discharge: 5.67m^3/s) was utilized. The main cooled-air flow was driven by a fan (0.75kw, 1400r.p.m) which was installed at the outlet side of the test section, and whose flow rate was controlled by a controlling valve and whose discharge was measured by a calibrated orifice meter. Cooling in the systems of the coolant flow and the cooled-air flow was performed by use of a refrigerator (R-22, 7.5kw, 1470r.p.m.).

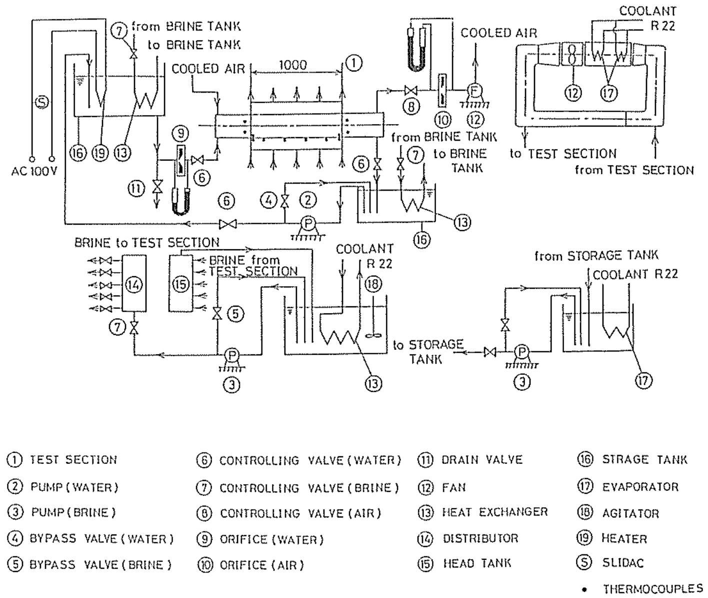

Fig.1 Schematic drawing of experimental apparatus.

2 . 2 Experimental Procedures

Temperature and flow rate of inlet water into the test section were set at the prescribed values, respectively, and the water level in the tube was controlled to be a select level by use of a weir installed at outlet of the test section. At the same time, the water level of storage tank, which was installed at the inlet side of the test section, was kept uniform by a controlling valve of a by-pass route. After which, the temperature and flow-rate controlled air was led into the test section. Observations of the ice layer developing along the tube wall were performed through a pair-glass window flange installed at the entrance of the test section. At the selected time, the water flow, the cooled-air flow, and the brine flow were stopped at the same time using the controlling valves, respectively. After which, the brine was removed from the test section and the water was poured in return for the brine. The ice deposit removed from the test section was cut down by a heated nichrome wire of 0.6mm in diameter at the axial positions of 200, 500 and 800mm, respectively. The ice pieces were filmed, respectively, and their negative films were enlarged to measure the local thickness of ice layer. These steps were successively repeated at the selected times, respectively.

In the present experiments, the freeze-off onset was defined as the state when the water-flow rate through the test section began to decrease (this corresponded to the time when the water level of the storage tank started to increase). The mean velocities of the water and air at the entrance of the test section were determined by dividing the flow rates by the cross section area filled with the fluids, respectively.

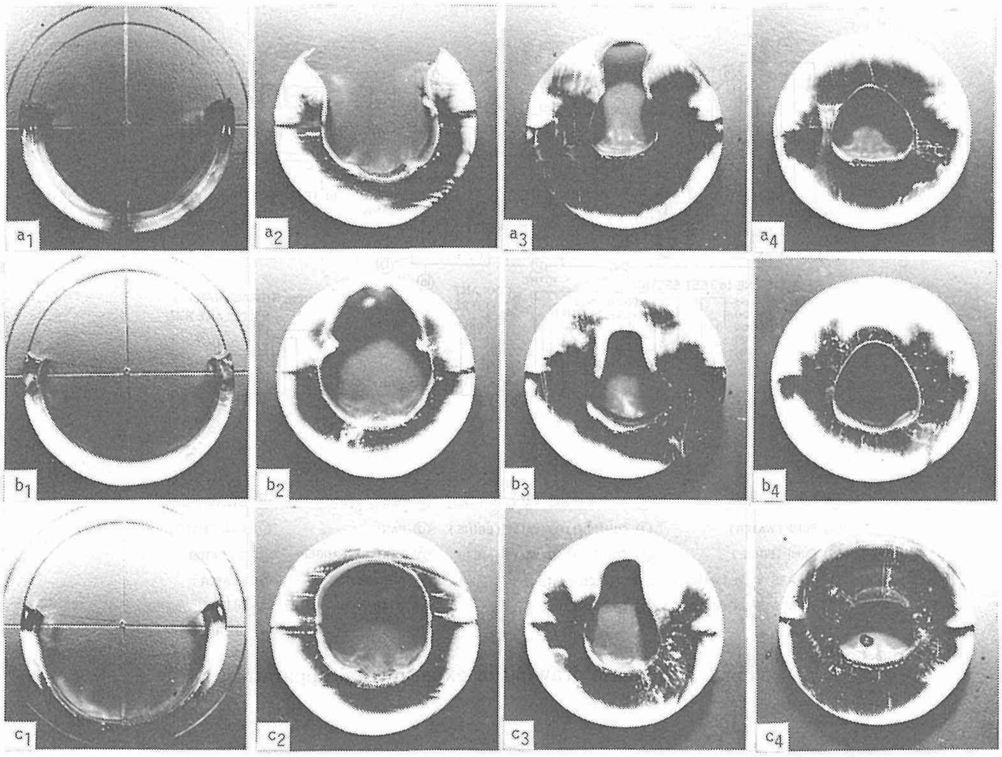

Fig.2 The effect of water velocity on freezing behavior.
$H=32$mm, $T_w=-10$°C, $u_a=1.46$m/s, $u_w=0.17$m/s ;
$L=200$mm ; a_1 10 minutes lapse ; a_2 50 ; a_3 90 ; a_4 100.
$L=500$mm ; b_1 10 minutes lapse ; b_2 50 ; b_3 90 ; b_4 100.
$L=800$mm ; c_1 10 minutes lapse ; c_2 50 ; c_3 90 ; c_4 100.

3. Results and Discussion

3 . 1 Freezing Behaviors in a Circular Tube

Figs.2 and 3 show the freezing behaviors in a circular tube for water velocities of 0.17 and 0.41m/s, respectively. As indicated in Fig.2, the ice-layer thickness along the upper tube wall increases from the entrance region of the test section ($L=200$mm) to the exit one ($L=800$mm) after 50 minutes since the experiment started. When 90 minutes elapsed as shown in Figs.2 a_3, b_3, and c_3, the shapes of the cross sectional area of the flow path exhibit a shape akin to a gourd. This may be because the ice layer along the upper tube wall begins to increase after the ice layer below the water surface has grown up sufficiently. In the case of higher water velocities (Fig.3), it is observed that the ice layer along the upper pipe wall has attained full growth after 50 minutes of cooling, which may make the lower part of ice layer in the tube melt, thus resulting in the decreasing of the ice-layer thickness at the lower part of the tube (see Figs.3 a_3, and c_3 : Figs.3 a_4, b_4, and c_4).

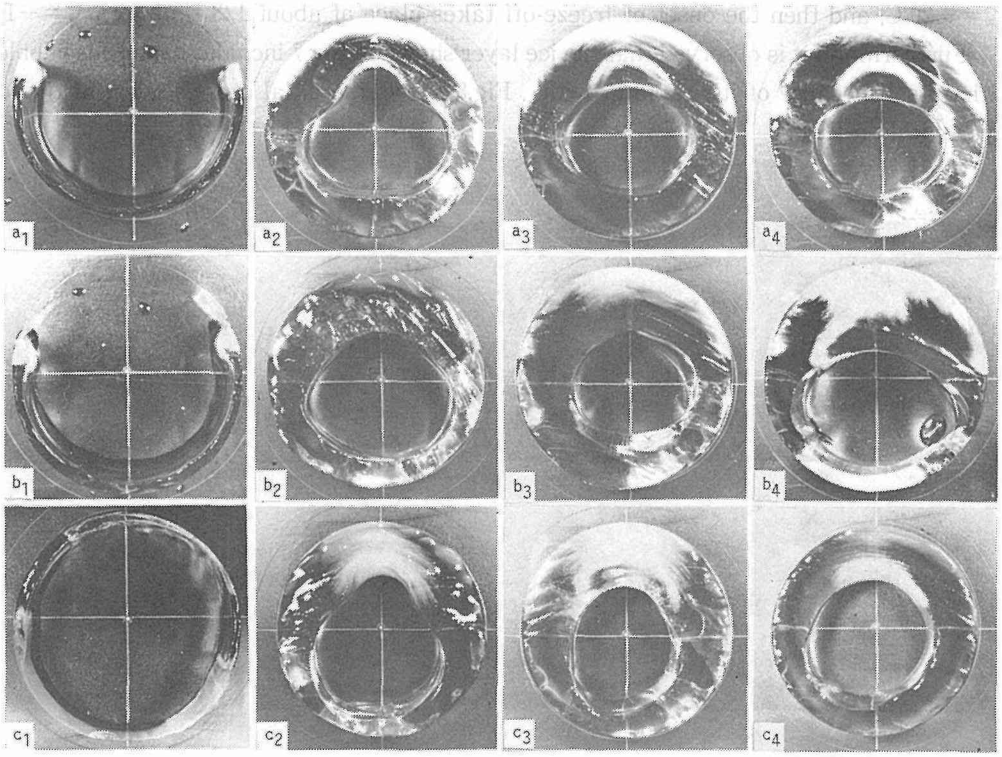

Fig.3 The effect of water velocity on freezing behavior.
$H=32mm$, $T_w=-10°C$, $u_a=1.46m/s$, $u_w=0.41m/s$;
$L=200mm$; a_1 10 minutes lapse ; a_2 50 ; a_3 90 ; a_4 118.
$L=500mm$; b_1 10 minutes lapse ; b_2 50 ; b_3 90 ; b_4 118.
$L=800mm$; c_1 10 minutes lapse ; c_2 50 ; c_3 90 ; c_4 118.

Figs.4 and 5 demonstrate the effect of air velocity on freezing behavior in a tube. When the air velocity is small, no ice layer is observed along the upper tube wall after 50 minutes of cooling (Figs. 4 a_2, b_2, and c_2). On the other hand, when the air velocity is large the ice layer is found to have developed along the upper tube wall after 50 minutes of operation (Figs.5 a_2, b_2, and c_2). Comparing the ice layer after 90 minutes of cooling shown in Fig.4 (see Figs.4 a_2, b_2, and c_2), it is found that in spite of same water velocity, the ice layer along lower tube wall increases with the decrease in air velocity, while the ice layer along upper tube wall increases with the increase in air velocity.

Figs.6 and 7 present the freezing behaviors for $T_w=-10°C$ and $-20°C$, respectively. From the ice-layer thickness after 50 and 90 minutes of cooling (Fig.6), it is observed that the ice-layer thickness along the lower tube wall decreases due to the growth of the ice layer along the upper tube wall for $T_w=-10°C$. On the other hand, it is revealed for $T_w=-20°C$ that the ice layer along the lower tube wall does not decrease from the start of cooling to the onset of freeze-off (see Fig.7). As shown in Figs.7 a_1, b_1, and c_1, the ice layer already starts to grow along the upper pipe wall after 10 minutes of cooling for

$T_w = -20$°C, and then the onset of freeze-off takes place at about 1/3 time for $T_w = -10$° C. Furthermore, it is observed that the ice layer shown in Fig.7 includes numerous bubbles within itself because of it's rapid growth. Fig.8 shows the axial cross section of the ice layer within a tube.

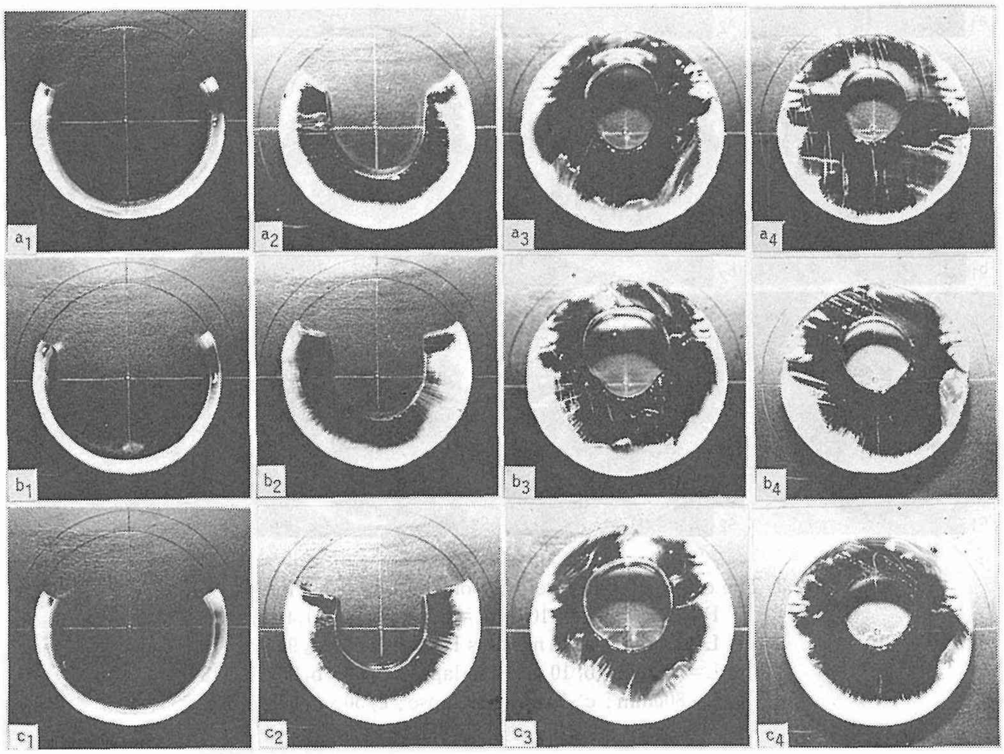

Fig.4 The effect of air velocity on freezing behavior.
$H = 48$mm, $T_w = -10$°C, $u_a = 0.40$m/s, $u_w = 0.17$m/s ;
$L = 200$mm ; a_1 10 minutes lapse ; a_2 50 ; a_3 90 ; a_4 123.
$L = 500$mm ; b_1 10 minutes lapse ; b_2 50 ; b_3 90 ; b_4 123.
$L = 800$mm ; c_1 10 minutes lapse ; c_2 50 ; c_3 90 ; c_4 123.

3 . 2 The effect of water velocity on growth of ice layer

Figs.9 and 10 show the effect of water velocity on the ice-growth behaviors for $u_a = 0.40$ and 1.12m/s, respectively. In the figures, $\phi = 0$ deg. denotes the top of the tube wall and $\phi = 180$ deg. the bottom of the tube wall.

In Fig.9, it is shown that the ice-layer thickness of the bottom for $u_w = 0.41$ and 0.35m/s decrease after 50 and 90 minutes of cooling, respectively. From the figure, it is also seen that for the higher water velocities the time when the ice-layer thickness of the bottom decreases tends to become short. This phenomenon may be assumed on the basis that the heat-transfer coefficient between water and ice layers increases due to an increase in water

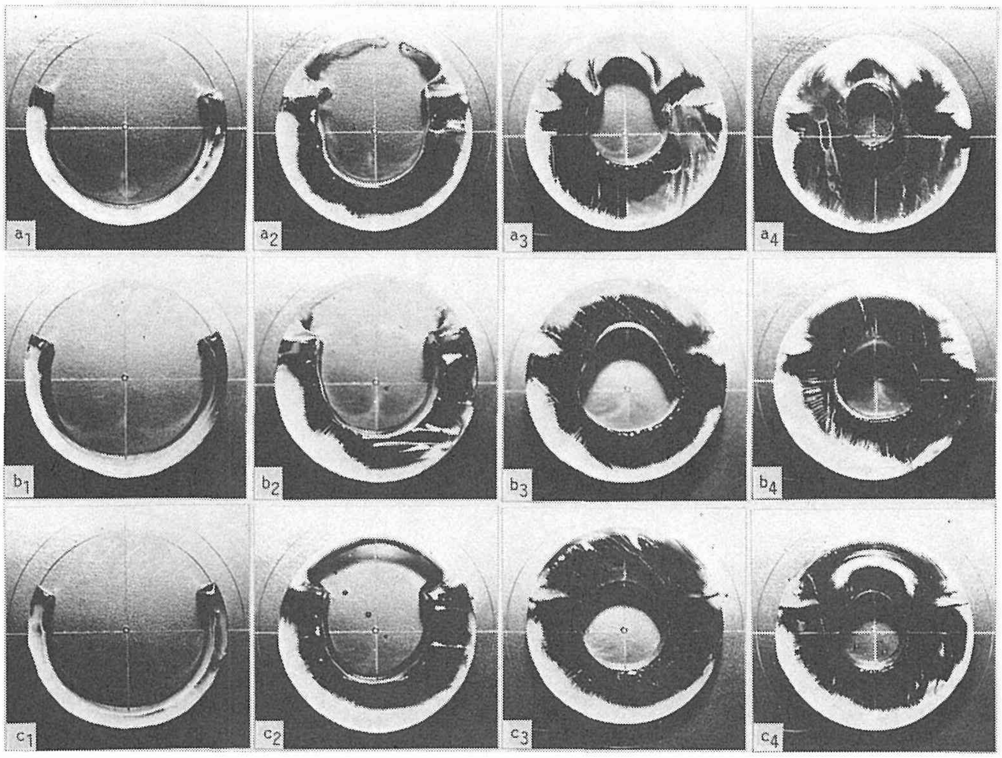

Fig.5 The effect of air velocity on freezing behavior.
$H=48mm$, $T_w=-10°C$, $u_a=1.12m/s$, $u_w=0.17m/s$;
$L=200mm$; a_1 10 minutes lapse ; a_2 50 ; a_3 90 ; a_4 122.
$L=500mm$; b_1 10 minutes lapse ; b_2 50 ; b_3 90 ; b_4 122.
$L=800mm$; c_1 10 minutes ; apse ; c_2 50 ; c_3 90 ; c_4 122.

velocity based on a decreasing sectional area for water flow since the water-flow rate is constant.

In Fig.10, it may be seen that the ice-layer thickness of the top in a tube for $u_w=0.35m/s$ is thinner than that for $u_w=0.41m/s$. This phenomenon is considered as follows. Primarily, the ice layer along the upper tube wall starts to grow due to a splashing of the water droplets based on ripples which take place at an air-water interface as the water level rises due to the growth of ice along the tube wall. However, since the water velocity is too fast, the time at which the main water flow directly contacts with the upper tube wall increases, thus, the heat-transfer coefficient between the ice layer along the upper tube wall and the stream of water increases. In Figs.9 and 10, it is of great interest to note that for $u_w=0.41m/s$ the ice layer thickness along the lower tube wall increases again after it initially decreased. However, the reason for this phenomenon has not yet been resolved.

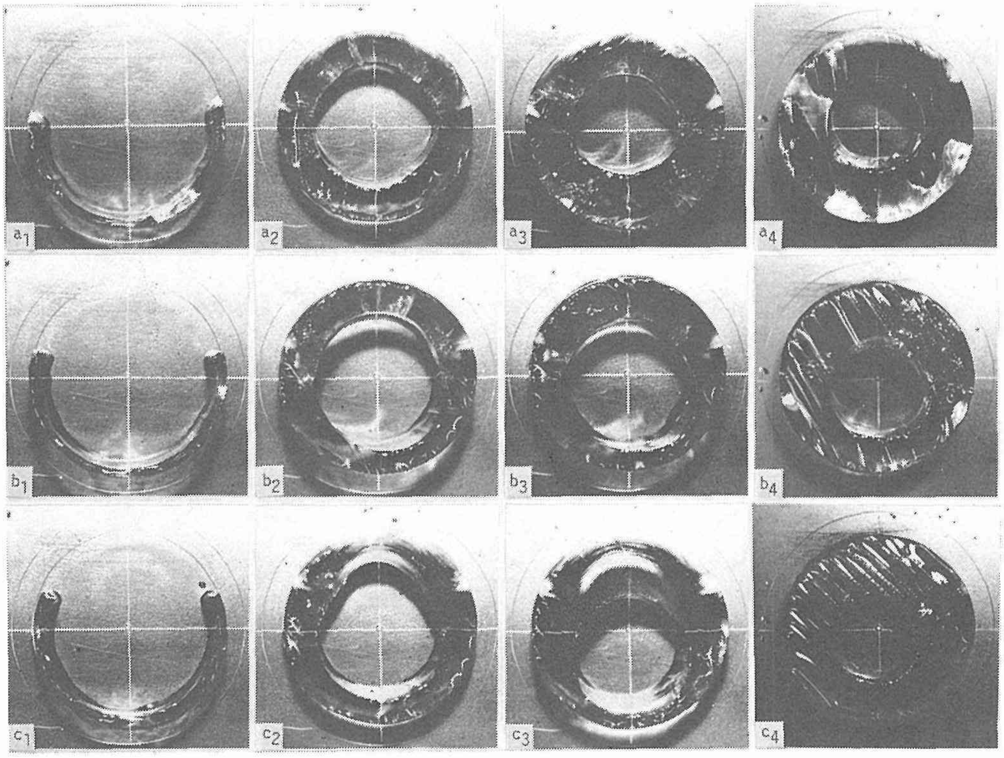

Fig.6 The effect of tube-wall temperature on freezing behavior.
$H=48mm$, $T_w=-10°C$, $u_a=1.12m/s$, $u_w=0.41m/s$;
$L=200mm$; a_1 10 minutes lapse; a_2 50; a_3 90; a_4 130.
$L=500mm$; b_1 10 minutes lapse; b_2 50; b_3 90; b_4 130.
$L=800mm$; c_1 10 minutes lapse; c_2 50; c_3 90; c_4 130.

3 . 3 The effect of air velocity on growth of ice layer

Figs.11 and 12 indicate the effect of air velocity on the development of the ice layer for $u_w=0.35$ and 0.41m/s, respectively. In the figures, the ice-layer thickness at the top of the tube wall increases with the increasing air velocity. This may be attributed to the fact that the faster the air velocity, the stronger the splashing of the water droplets based on the ripples which take place at an air-water interface, thus resulting in a quick increase of the ice layer at the upper tube wall.

Fig.13 demonstrates the state of an air-water interface which is accompanied by ripples whose height is observed to increase as they approach the outlet of the test section. As understood from the visual observations mentioned above, the ice layer along the upper tube wall is somewhat whitish because of an abundance of air bubble which is included (see Figs.5 a_3, b_3, and c_3). Under the conditions of $H=48mm$, $u_a=1.46m/s$, $u_w=0.35m/s$, and $T_w=-10°C$, it was found that the ice-layer density along the upper pipe wall is smaller than that along the lower tube wall by about 6%.

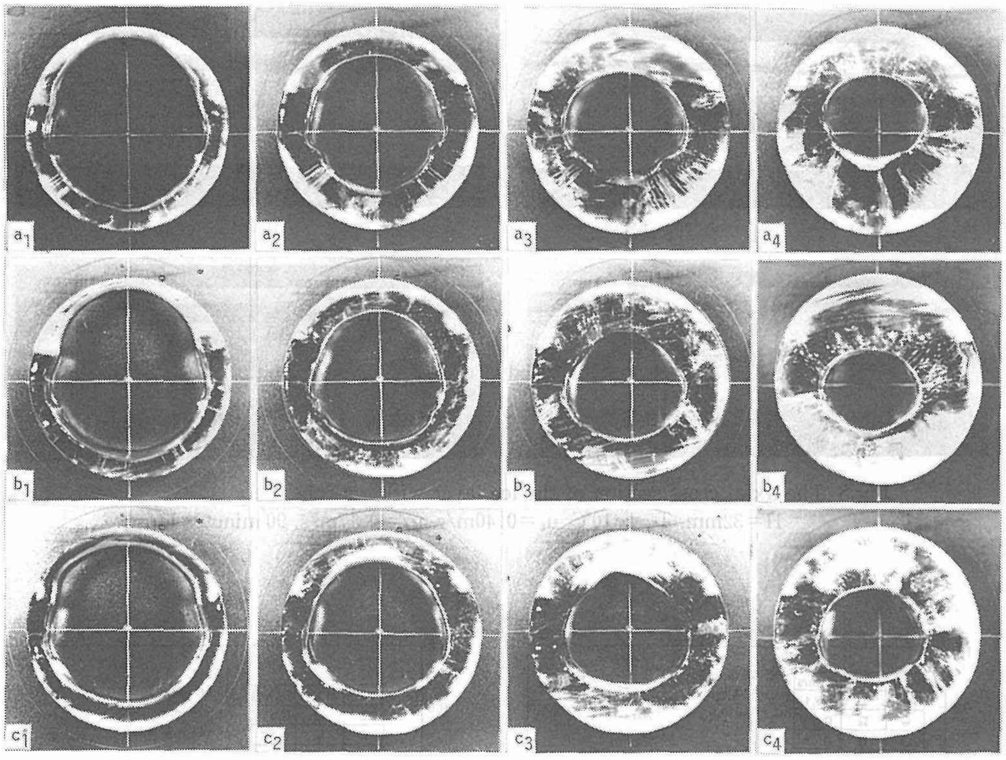

Fig.7 The effect of tube-wall temperature on freezing behavior.
$H=48\mathrm{mm}$, $T_w=-20^\circ\mathrm{C}$, $u_a=1.12\mathrm{m/s}$, $u_w=0.41\mathrm{m/s}$;
$L=200\mathrm{mm}$; a_1 10 minutes lapse; a_2 20; a_3 30; a_4 47.
$L=500\mathrm{mm}$; b_1 10 minutes lapse; b_2 20; b_3 30; b_4 47.
$L=800\mathrm{mm}$; c_1 10 minutes lapse; c_2 20; c_3 30; c_4; 47.

In Fig.11, it is elucidated that the ice-layer thickness along the lower tube wall decreases after about 90 minutes of cooling, while in Fig.12 the ice-layer thicknesses for $u_a=1.46$ and 0.40m/s decrease after 30 and 50 minutes of cooling, respectively. These phenomena are considered in the following manner. In the experimental condition of Fig. 12, as the ice grows along the upper tube wall, the water-flow is pushed against the bottom of the tube and is also accelerated according to the higher air flow, thus resulting in an increased water velocity. On the other hand, for a smaller water velocity (Fig.11), the effect mentioned above is considered to be small compared with that for greater water velocity (Fig.12).

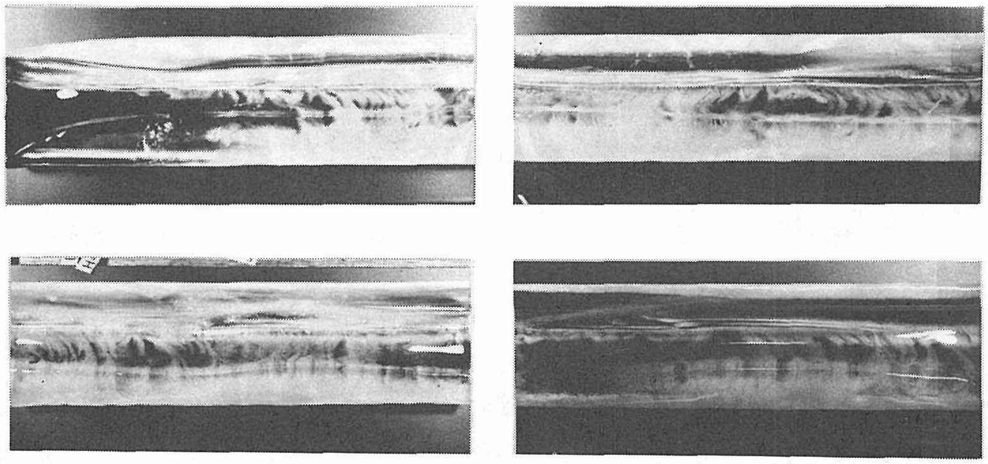

Fig.8 The axial cross section of the ice layer within a tube.
H=32mm, T_w=-10°C, u_a=0.40m/s, u_w=0.17m/s, 90 minutes lapse.

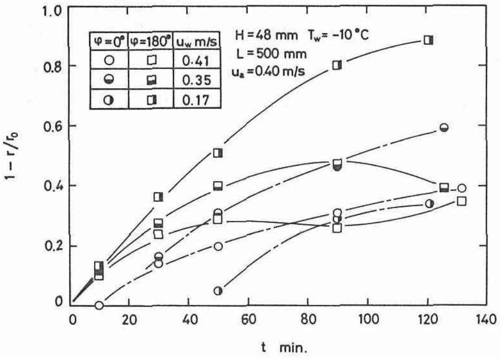

Fig.9 The effect of water velocity on ice-growth behavior.

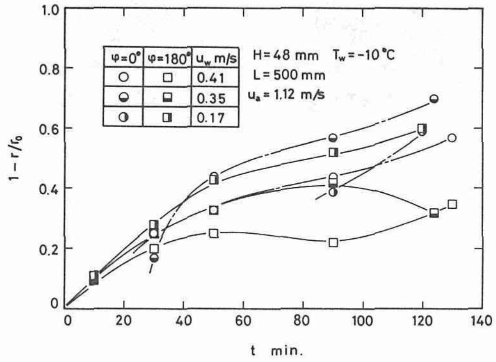

Fig.10 The effect of water velocity on ice-growth behavior.

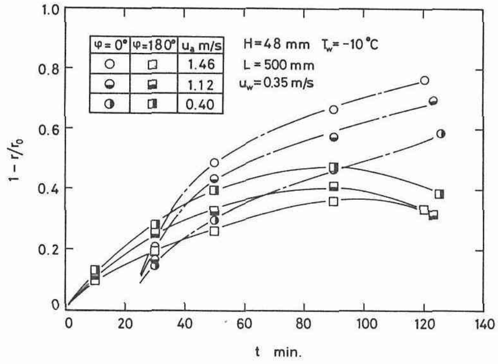

Fig.11 The effect of air velocity on development of ice layer.

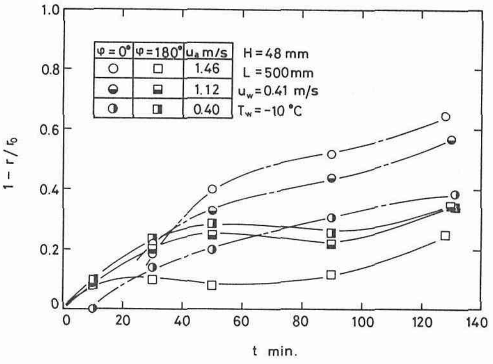

Fig.12 The effect of air velocity on development of ice layer.

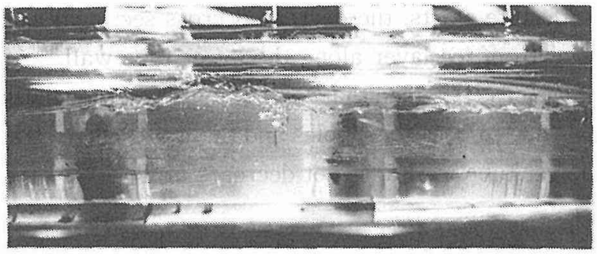

Fig.13 The state of an air-water interaface.

3 . 4 The effect of water velocity on onset of freeze-off state

Fig.14 shows the effects of various parameters on the onset of the freeze-off state. It can be clearly seen from the figure that both the larger air velocity and the smaller the water velocity, the sooner the onset of the freeze-off state takes place. As pointed out earlier, this seems to be due to the fact that the larger air velocity causes intense ripples at the air-water interface, thus resulting in a great deposit of ice along the upper tube wall. And for small water velocity the ice layer along the tube wall under the water surface grows rapidly.

3 . 5 The effect of tube-wall temperature on growth of ice layer

Fig.15 shows the effect of tube-wall temperature on the growth of ice layer. Experiments were carried out under the conditions of $T_w=-10°C$, and $-20°C$ for $H=48mm$, $L=500mm$, $u_a=1.46m/s$ and $0.35m/s$, respectively. In the case of $T_w=-20°C$, the onset of freeze-off state is found to start at the time of one-third that for $T_w=-10°C$. This is attributable to the greater growth of the ice layers along both the upper and lower pipe walls based on the lower tube-wall temperature. For $T_w=-10°C$, the ice layer along upper tube wall is thicker than the lower one after 30 minutes of cooling, while for $T_w=-20°C$, the upper one is thinner than the lower one until immediately about 40 minutes has elapsed when the freeze-off state starts. This phemonenon may be on the basis that before

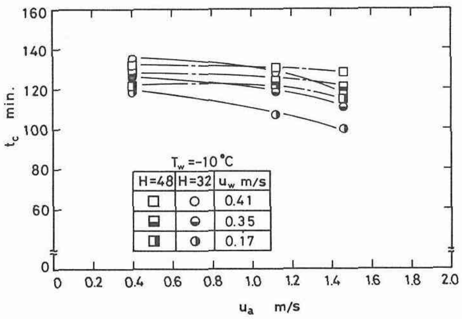

Fig.14 The effects of various parameters on onset of freeze-off state.

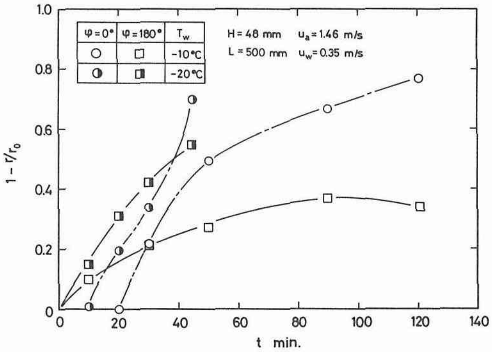

Fig.15 The effect of tube-wall temperature on growth of ice layer.

the onset of freeze-off state starts, the decreased cross sectional area for water and air flows disturbs the growth of ice layer along the lower tube wall.

As mentioned above, it is revealed that for $T_w = -20°C$ although the ice layer at the top of the tube wall grows due to both the ripples and the waves at the water-air interface, the ice layer along the lower tube wall does not decrease at $T_w = -10°C$ because of the lower tube-wall temperature.

4. Conclusions

According to the experimental results of the present investigation concerning the transient freezing characteristics of layered air-water flow in a horizontal circular tube, the following conclusions may be drawn:

(1) The water level rises based on the growth of ice along the tube wall which is covered with the water and then the ice layer along upper part of the tube wall grows because of the splashing of the water droplets based on ripples which take place at an air-water interface.

(2) At tube-wall temperature of $T_w = -10°C$, the growth of the ice layer along upper tube wall increases with the increase in air and water velocities. As a result, the ice layer thickness along the lower tube wall decreases as the time elapses. However, the upper ice-layer thickness decreases for the water velocities above the prescribed one.

(3) The larger the water velocity and the smaller the air velocity, the earlier the onset of freeze-off state.

(4) At tube-wall temperature of $T_w = -20°C$, the ice layer along the lower tube wall does not decrease based on the effect of the ice layer along the upper tube wall unlike at $T_w = -10°C$ because of great rapid growth of the ice layer.

Acknowledgements

The authors are deeply indebted to Professor Emeritus N. Seki, the president of Hokkaido Polytechnical College, for his encouragement in preparing the manuscript and to Mr. M. Satoh for his help in the experiments.

References

1) Zerkle, R.D., Sunderland, J.E.: Trans. ASME. J. Heat Transfer, 90 (1968), 183.
2) Thomason, S.B. et al.: Trans. ASME. J. Heat Transfer., 100 (1987), 387.
3) Gilpin, R.R., Hirata, T.: Heat Transfer-San Diego, AIChE Sympo. Series 189., 75 (1979), 89.
4) Seki, N. et al.: Trans. JSME. 49-446 (1983), 2172.
5) Seki, N. et al.: Trans. ASME. J. Heat Transfer., 10 (1984), 498.
6) Seki, N. et al.: Wärme-Stoffübertrag., 18 (1984), 117.
7) Fukusako, S. et al.: Trans. JSME. 51-461 (1985), 376.