Fundamental Study on Continuous Ice Making Using Flowing Supercooled Water*

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Basic experiments were carried out concerning the possibility of continuous ice making in supercooled water in a forced flow. In the experiments, the critical conditions of ice formation and stability of supercooled water flowing in cooling tubes were examined for four sets of tube dimensions under various Reynolds numbers. It was established that two ice growth modes of annular ice and dendritic ice appeared in the tubes according to the degree of supercooling. Nondimensional correlation equations of supercooling for ice nucleation in laminar and turbulent flow regions were derived as a function of the ratio of the thermal boundary layer thickness to the characteristic length. The latter is defined as the distance from the position where the mixing average temperature of the flowing water falls below freezing point, to the tube exit.

Key Words : Freezing, Cold Energy Storage, Supercooling, Ice Formation, Forced Convection

1. Introduction

In recent years various methods of ice making, which are represented by static and dynamic methods, have been proposed to utilize a cold heat storage system⁽¹⁾. Among them, the method using flowing supercooled water, attempted in the present work, is promising, because it can overcome some faults found in former methods. In the present method, water flowing over the cooling surface is supercooled, and minute ice crystals are continuously formed downstream of the surface by introducing an artificial nucleating agent. Thus, the stability of flowing supercooled water on the cooling surface and the degree of supercooling, which is defined as the temperature difference between supercooled water and the freezing point, are predominant factors in the capability of ice making in the present method.

For supercooled quiescent water, several experiments have been performed. Bigg⁽²⁾ examined supercooling of a water droplet suspended between two immiscible liquids and found a trend of decreasing degree of supercooling with increasing droplet diameter. Saito et al.⁽³⁾ reported the surface property effects of the cooling wall on the supercooling phenomena, by applying statistical techniques to the data analysis. They noted that the degree of supercooling increased with the decrease of surface roughness, whereas the surface quality had little effect on ice nucleation. For the effect of the cooling rate of water on ice nucleation, Hobbs⁽⁴⁾ found little effect in the range less than 1 °C/min.

On the other hand, for supercooled water in a forced flow, Arora and Howell⁽⁵⁾ investigated the stability of supercooled water in a turbulent flow inside a tube, but no appreciable success was achieved in maintaining a constant degree of supercooling because of the imperfection in the experimental cooling conditions. Mukushi and Takahashi⁽⁶⁾ measured the degree of supercooling for water flowing in cooled copper tubes of various inner diameters. They showed that the maximum degree of supercooling varied with

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the flow velocity and the ratio of the tube length to the inner tube diameter. Gilpin⁽⁷⁾ visualized the freezing process of water flowing in a cooled tube and found that two ice growth modes, annular ice and dendritic ice modes, appeared in the cooling tube according to the degree of supercooling.

A survey of the literature reveals that little research has been done to investigate the critical conditions of ice formation and stability of supercooled water in forced flow. The objectives of the present work are to obtain such information and to clarify the effects of various parameters on stably maintaining a constant degree of supercooling and the ice-making efficiency in the present method. Experiments on the stability of flowing supercooled water are performed for four sets of tube dimensions under various Reynolds numbers. The effects of the macroscopic factors on ice formation in supercooled water and the ice-making efficiency are investigated on the basis of visual observations of ice formation and data analysis.

Nomenclature

- C : nondimensional variable
 C_p : specific heat of water
 d_i, d_o : inside diameters of inner and outer tubes
 L : latent heat of solidification of water
 l : length of cooling section
 l_s : distance from the position where the mixing average temperature of flowing water reaches the freezing point to cooling tube exit
 P : entrance water pressure
 Q_w : flow rate of water
 r_n : boundary layer thickness
 T_f : freezing point
 T_n : critical nucleation temperature
 T_{in}, T_{out} : temperature of water at the entrance and exit of tube
 T_w : average inner wall temperature
 ΔT : degree of supercooling
 ΔT_i : maximum degree of supercooling for quiescent water ($=6.8\text{ K}$)
 ΔT_s : degree of supercooling based on T_{out} , ($=T_f - T_{out}$)
 ΔT_w : degree of supercooling based on T_w , ($=T_f - T_w$)
 t : tube wall thickness; time elapsed
 W : net ice mass produced per minute
 v : average velocity of water
 Pr : Prandtl number of water
 Re : Reynolds number ($=vd_i/\nu$)
 $\Delta\mu$: chemical potential difference between solid and liquid phases ($=L\Delta T/T_f$)
 $\Delta\mu_s$: critical chemical potential difference of

- supercooled quiescent water ($=L\Delta T_i/T_f$)
 $\Delta\mu_w$: chemical potential difference of flowing supercooled water ($=L\Delta T_w/T_f$)
 δ : thermal boundary layer thickness
 ν : kinematic viscosity of water
 η : ice making efficiency ($=W/Q_w \times 100$)
 η_{th} : theoretical ice making efficiency ($=C_p\Delta T/L \times 100$)

2. Experimental Apparatus and Procedure

Figure 1 schematically shows the experimental apparatus, which consisted of forced circulation loops of test water and coolant. The test section is a horizontal double-tube heat exchanger with the test water flowing in the inner stainless steel tube and the coolant flowing concurrently in the annulus. The test water stored in the lower part of an ice-making vessel ② flowed into the inner tube of the test section via a rustproof pump ④, two fine filters ⑤, a rotor meter ⑥ and a cooling heat exchanger ⑦. The water was supercooled in the test section. The supercooled water drained from the test section in the form of a water column and collided with a wire net ⑨ (# 50) set in the lower part of the ice-making vessel. Minute ice crystals were formed on the net due to the ice nucleation resulting from the collision energy or seeding using some ice crystals placed on the net in advance, while the remaining water without ice formation drained to the lower part of the ice-making vessel. The test water was tap water by filtered through an ion-exchange column, and its specific resistance of $10^6\ \Omega\text{cm}$ was at 20°C . In addition, to remove as much particulate matter as possible, the test water was filtered through a fine filter of $1\ \mu\text{m}$ pore diameter located at two positions in the test water loop. Ethylene glycol solution of 50 wt% was used as the coolant. The coolant temperature was regulated by the refrigeration system consisting of a refrigerator ⑬ and two coolant tanks ⑩, ⑪ to maintain a prescribed temperature within $\pm 0.05^\circ\text{C}$.

The inner tube of the test section consisted of an entrance section (length: 1.5 m), a cooling section (length: 3.8 m or 1.0 m) and a releasing section (length: 0.5 m). Three inner tubes with different inner diameters, d_i , of 4.5, 10.5 and 15.6 mm were used. The inner surface of the tubes were polished by the electrolytic-abrasive method in an attempt to avoid the effects of surface roughness on the supercooling phenomena. The maximum surface roughness was observed to be within $0.2\ \mu\text{m}$. In order to visualize the ice formation process in the tube, a transparent double-tube heat exchanger having an outer acrylic tube ($d_o = 50\text{ mm}$, $t = 2\text{ mm}$) and an inner Pyrex glass tube ($d_i = 15\text{ mm}$, $t = 2\text{ mm}$) was used. Its length was 3.8 m.

Fig. 1 Schematic diagram of experimental apparatus

The ice-making vessel (height $\times$ length $\times$ width = 720 mm $\times$ 1 300 mm $\times$ 720 mm) made of acrylic resin was surrounded by insulating materials having a thickness of 100 mm, and the inner temperature of the vessel was maintained at 0°C by a cooling unit ③ so as to avoid the melting of ice crystals formed on the net.

The coolant temperatures at the entrance and exit of the test section, as well as the entrance water temperature, were measured using 0.1-mm-diameter T-type thermocouples. Six wall thermocouples were embedded at 760 mm intervals from the cooling section entrance for the section with $l=3.8$ m. A T-type traversing thermocouple of 0.05 mm diameter was located about 30 mm downstream from the test section exit to measure the temperature distribution in the water column. A precision pressure sensor was located at the entrance of the test section to monitor

the pressure change in the tube during the freezing process. Some of the ice crystals formed on the net was dehydrated by a centrifugal separator set in a constant low temperature room (0°C), and the water content was obtained from the mass difference between before and after dehydration. As will be seen later, the ice-making efficiency was calculated from the net ice mass estimated from the measured data.

The experiments were carried out at a constant entrance water temperature of 0.1~0.2 °C and water flow rate was changed from 0.4 to 8.0 kg/min. Two experiments were performed. The first experiment was aimed at obtaining the critical conditions of ice formation of supercooled water in a forced flow. The temperature of the coolant flowing in the annulus was programmed to decrease at a constant cooling rate of 0.2 °C/min from 0°C. Cooling of the test water commenced while the temperatures and the pressure were

recorded. The test water was cooled until the occurrence of complete pipe blockage due to ice formation in the flowing supercooled water. Ice formation in the cooling tube was confirmed by observations of ice crystals at the tube exit and an increase in the water pressure, and then each measured value was adopted as the upper limits of the critical conditions of ice formation.

The other experiment was performed to obtain the stable conditions of ice formation and the ice-making efficiency. Continuous ice making was carried out at a constant degree of supercooling under various cooling conditions. The upper limits of the supercooling conditions under which continuous ice making for over four hours was achieved, was adopted as the lower limits of the critical conditions of ice formation. Measurements of the ice-making efficiency were performed several times during each experiment.

After the experiment, the test section was allowed to warm to $+1^{\circ}\text{C}$ and to stand at least three hours at the desired temperature before the next experiment.

3. Results and Discussion

3.1 Behavior of ice formation

In the present work, it was observed that ice crystals were continuously formed on the wire net from the supercooled water. Figures 2(a) and (b) show the behavior of ice formation observed at the degree of supercooling, ΔT_s , of 0.3 K and 2.1 K, respectively. ΔT_s is defined as

$$\Delta T_s = T_f - T_{out}, \quad (1)$$

Fig. 2 Behavior of ice making observed on wire net

Fig. 3 Ice crystals formed from flowing supercooled water

where T_f is the freezing point temperature and T_{out} denotes the temperature of the test water at the tube exit. In Fig. 2(a), it is found that ice crystals form an ice column growing in the upstream direction of the supercooled water. In contrast, at relatively high ΔT_s , as shown in Fig. 2(b), it is noted that the ice crystals are relatively dispersed over the wire net without formation of the ice column. The difference in the behavior is presumably caused by the structure of ice crystals, which varies with the degree of supercooling.

Figures 3(a) and (b) show the ice crystals observed at $\Delta T_s = 0.3$ K and 2.1 K, respectively. In Fig. 3(a), it can be seen that laminar ice crystals with low water content are formed. At relatively high ΔT_s in Fig. 3(b), however, the ice consists of minute granular crystals with high water content. The result is consistent with the previous findings on the structure of ice crystals formed from supercooled water, of Mukushi and Takahashi⁽⁶⁾, and it is also similar with respect to ice crystal habit in a diffusion chamber reported by Hallet and Mason⁽⁸⁾.

3.2 Ice growth modes in a cooling tube

It was observed that ice crystals were generated simultaneously with ice formation in the tube. Figures 4(a) and (b) are photographs showing the ice generated at the degree of supercooling, ΔT_w , of 0.9 K and 2.8 K, respectively. ΔT_w is defined as

$$\Delta T_w = T_f - T_w, \quad (2)$$

where T_w is the average inner wall temperature calculated from the water-to-coolant heat-transfer correlation equation⁽⁹⁾. In Fig. 4(a), it is observed that the generated ice consists of an annular ice shell of high density and dendritic ice filling in the annular ice shell. However, at relatively high ΔT_w , as shown in Fig. 4(b), it is found that the generated ice is of a dense matrix of dendritic ice with high water content and fluidity.

The ice growth modes in the cooling tube were observed in detail by using the transparent double-tube heat exchanger, and the freezing processes were recorded on a high-speed video system. The results of the visual observations revealed that the nucleation of dendritic ice almost always occurred near the exit of the cooling tube in the supercooled water adjacent to

Fig. 4 Photographs showing ice generated from tube exit

the wall surface. Figure 5 illustrates the typical ice growth mode observed at the degree of supercooling, ΔT_s , of 1.1 K. In Fig. 5(a), the sketch immediately after ice nucleation ($t=0.01$ sec) reveals that the dendritic ice rapidly grows out into the supercooled water and instantly spreads from the nucleation site along the cooling wall surface. After 1.0 sec, furthermore, the dendritic ice grows in the radial and axial directions of the tube, so that the flow rate of the water rapidly decreases due to the increase of flow resistance. At that time, detailed observation, as shown in Fig. 5(b), indicates that the dendritic ice attached to the cooling wall surface changes into a thin annular ice shell of high density, which gradually grows in the center of the tube with time. The growth velocity of the dendritic ice formed at the beginning was found to be about 80 mm/sec from the present visual studies. This value was greater than that for supercooled quiescent water⁽³⁾. This may be due to the fact that the heat transfer coefficient between solid and liquid phases in the flowing supercooled water is larger than that in the supercooled quiescent water, so that the latent heat release in the ice growth process is accelerated at the solid/liquid interface.

Figure 6 illustrates the time traces of both the pressure at the entrance of the test tube and the outer wall temperature during ice formation in the tube at the degree of supercooling, ΔT_w , of 0.9 K and 2.8 K, respectively, along with the sketches of the ice growth modes observed in the tube. In Fig. 6(a), the pressure first shows a steep rise owing to the nucleation of dendritic ice, then it follows a trend of large fluctuations due to several surges of the dendritic ice filling the annular ice shell formed in the vicinity of the

Fig. 5 Typical ice growth process in tube observed at $\Delta T_s = 1.1$ K

cooling wall surface. When complete blockage of the tube finally occurs, the pressure reaches the maximum value determined from the capability of the pump. For the outer wall temperature in Fig. 6(a), it is found that the temperature trace shows several fluctuating trends corresponding to the pressure trace, and the outer wall temperature gradually decreases after complete blockage. At relatively high ΔT_w , as shown in Fig. 6(b), however, the pressure rises sharply due to the nucleation of dendritic ice, and then it immediately reaches the maximum value without fluctuation, unlike low ΔT_w . This rapid blockage of the tube is associated with the fact that a large amount of dendritic ice appears in the cooling tube at the beginning owing to a high ΔT_w , and it immediately grows in the center of the tube. Consequently, it is established that two ice growth modes, annular ice and dendritic ice, appear in the cooling tube according to the degree of supercooling.

3.3 Critical conditions of ice formation

Effects of flow velocity and tube dimensions on ice nucleation in flowing supercooled water are discussed in this section. Fletcher⁽¹⁰⁾ suggested that ice

Fig. 6 Time traces of entrance water pressure and outer wall temperature during ice formation in tube, and sketches of two basic tube blockage modes

Fig. 7 Ice nucleation model of flowing supercooled water in tube

nucleation immediately occurs when the size of a cluster of water molecules exceeds the critical radius which is derived as a function of the chemical potential difference between solid and liquid phases, $\Delta\mu (= L\Delta T/T_f)$, and surface free energy. Whether or not ice nucleation will occur in supercooled water depends on the degree of supercooling, ΔT , and its probability will increase with ΔT . In addition, if the ice formation occurs due to heterogeneous ice nucleation, as can be seen in the present study, it is considered that several factors, such as impurities in water, temperature distribution in supercooled water and characteristics of the cooling surface, present a catalytic effect on ice nucleation.

Based on the physical background of ice nucleation and the visual observations of ice formation in the cooling tube, the ice nucleation model for flowing supercooled water inside a cooling tube is adopted as shown in Fig. 7. The model assumes a linear temperature profile in the thermal boundary layer. With flow penetration through the cooling tube, the degree of supercooling increases, so that a cluster of water molecules grows along the established molecular chain, and also, the number of clusters increases. If the size of the cluster exceeds the critical radius as mentioned earlier, ice nucleation will occur immediately in the supercooled water. Thus, the probability of ice nucleation near the cooling tube exit becomes higher than that at any other site, as can be seen in the visual observations. For ice crystals to begin forming, the model assumes that ice nucleation ordinarily occurs in the vicinity of the cooling surface, and the temperature within a distance, r_n , from the cooling wall surface must be below a critical nucleation temperature, T_n . If the cluster having the same order of the critical radius exists within r_n , the probability of

Fig. 8 Variation of critical degree of supercooling, ΔT_w , based on average inner wall temperature with Reynolds number Re

ice nucleation will increase with increasing temperature gradient in the thermal boundary layer, because of the effects of the cooling wall surface and the thermal fluctuations based on the temperature gradient in the thermal boundary layer. The value of r_n will depend on the thermal boundary layer thickness, δ . A high probability of ice nucleation in the vicinity of the cooling surface can also be seen in the previous investigation on supercooled quiescent water by Saito et al.⁽³⁾

Figure 8 shows the critical conditions of ice formation for three sets of tube inner diameters plotted on the coordinates of the degree of supercooling, ΔT_w , based on the average inner wall temperature and Reynolds number, $Re (= vd_i/\nu)$. It is observed that ΔT_w decreases with increasing Re , and the decreasing trend becomes more marked for larger Re . This may be attributed to the fact that increasing Re causes an increase in both the temperature gradient in the thermal boundary layer and the quantity of the supercooled water flowing in the tube. Thus ice nucleation

is accelerated in the vicinity of the cooling wall surface. For the same Re , data show a trend of increasing ΔT_w with d_i . A similar trend was observed by Arora and Howell⁽⁶⁾. Slight scattering of the present data is observed, which may be due to the effects of some other microscopic phenomena on ice nucleation.

Figure 9 shows the same data as shown in Fig. 8, plotted on the coordinates of the degree of supercooling, ΔT_w , and the thermal boundary layer thickness at the cooling tube exit, δ . The value of δ is obtained by the following process. At the turbulent flow region ($Re > 3000$), the viscous layer thickness is adopted as δ , because the steep temperature gradient is considered to exist in the viscous layer. From Ref. (9), the value of δ in the turbulent flow inside a circular tube is given by

$$\delta = 5d_i(2f)^{0.5}/Re, \quad (3)$$

where f is the Blasius friction factor given by $f = 0.079/Re^{1/4}$. At the laminar flow region ($Re \leq 3000$), assuming a fully developed velocity profile, the value of δ is obtained by solving an energy equation, and the result is expressed as

$$\delta = (d_i/2)(3.03 \times 10^{-7} Z^{-5.205} + 138.0)^{-1/15}, \quad (4)$$

where $Z = 2l/d_i/(RePr)$

An inspection of Fig. 9 reveals that ΔT_w tends to increase with δ regardless of the turbulent and laminar flow regions. However, a different dependence of ΔT_w on δ is observed for each flow region. In addition, there is a distinct demarcation in the present data. The solid lines in Fig. 9 indicate the limiting regions obtained from the measured values of ΔT_w for each flow region. Above the upper solid lines for each flow region, ice formation always occurs in the flowing supercooled water, but below the lower solid lines, no

ice nucleation occurs.

Some effective parameters are introduced to predict the critical conditions of ice formation in the flowing supercooled water inside the cooling tube, as follows. In order to determine that the characteristics of the test water are one of the dominant factors, preliminary experiments on quiescent supercooled water were performed at various cooling rates ($0.01 \sim 0.2^\circ\text{C}/\text{min}$) using the same kind of test water (volume: 100 cm^3) contained in a stainless-steel tube (i.d.: 50 mm , length: 70 mm) having the same characteristics as that used in the flow experiment. The maximum degree of supercooling, ΔT_i , of 6.8 K was obtained. The critical chemical potential difference for the supercooled quiescent water is given by

$$\Delta\mu_s = L\Delta T_i/T_f, \quad (5)$$

where L is the latent heat of solidification, and T_f is the freezing point ($T_f = 273.15\text{ K}$). The value of ΔT_i in Eq. (5) was determined on the basis of the preliminary experiment as 6.8 K , while for flowing supercooled water, taking the ice nucleation occurring ordinarily in the vicinity of the cooling wall surface into consideration, the chemical potential difference is defined as

$$\Delta\mu_w = L\Delta T_w/T_f, \quad (6)$$

where ΔT_w is the degree of supercooling based on the average inner wall temperature. As is evident from Fig. 9, the thermal boundary layer thickness, δ , is considered to be one of the effective parameters accounting for the effects of the temperature gradient, in the vicinity of the cooling wall surface, on ice nucleation. In addition, the ice nucleation model shown in Fig. 7 assumes that the probability of ice nucleation increases with the degree of supercooling. Thus, the length l_s , defined as the distance from the position where the mixing average temperature reaches the freezing point, to the cooling tube exit, is adopted as the effective parameter. The value of l_s is calculated from the water-to-coolant heat-transfer correlation equation⁽⁹⁾.

Figure 10 presents the relationship between the nondimensional parameters, $\Delta\mu_w/\Delta\mu_s$ and δ/l_s , obtained for various tube dimensions. The ordinate, $\Delta\mu_w/\Delta\mu_s$, indicates the nondimensional degree of supercooling based on the chemical potential difference for the flowing and quiescent supercooled water. An overall inspection of Fig. 10 reveals that the $\Delta\mu_w/\Delta\mu_s$ decreases with decreasing δ/l_s . This is because the probability of ice nucleation increases with increasing l_s or decreasing δ , so that ice nucleation in supercooled water occurs at relatively low ΔT_w . The value of $\Delta\mu_w/\Delta\mu_s$ is scattered between the upper and lower solid lines in the turbulent and laminar flow regions shown in Fig. 10, because of the

Fig. 9 Variation of critical degree of supercooling, ΔT_w , based on average inner wall temperature with thermal boundary layer thickness at tube exit δ

Fig. 10 Relationship between nondimensional parameters $\Delta\mu_w/\Delta\mu_s$ and δ/l_s

Fig. 11 Comparison of ice-making efficiency data for various tube dimensions with the prediction of Eq. (10)

effects of some other microscopic phenomena on ice nucleation, any one of which can trigger the complex phenomenon of ice formation. Therefore, taking the scattering of the present data into consideration, correlation equations for the upper and lower critical conditions of ice formation are expressed as below.

● Turbulent flow region

$$Re = 3\,000 \sim 8\,000, \delta/l_s = 2.0 \times 10^{-5} \sim 3.0 \times 10^{-4}$$

$$\Delta\mu_w/\Delta\mu_s = C(\delta/l_s)^{0.887} \quad (7)$$

where $C=426$ for lower limit, $C=1\,337$ for upper limit

● Laminar flow region

$$Re = 500 \sim 3\,000, \delta/l_s = 3.0 \times 10^{-4} \sim 1.0 \times 10^{-2}$$

$$\Delta\mu_w/\Delta\mu_s = C(\delta/l_s)^{0.677} \quad (8)$$

where $C=13.4$ for lower limit, $C=43.0$ for upper limit.

Equations (7) and (8) reveal that, in the range between the upper and lower limits, ice formation may occur in the cooling tube, namely, in the unstable region of supercooling. On the other hand, above the upper limit, complete blockage of the tube occurs due to ice formation in the supercooled water, and below

the lower limit, that is, the stable region of supercooling, no ice nucleation appears. The broken lines in Fig. 10 may show the predictions for a larger δ/l_s range than the present experimental ranges, since the actual phenomena probably resemble the quiescent water result ($\Delta\mu_w = \Delta\mu_s$). Thus, the stability of supercooling in lower flow velocity regions, which include natural convection regions, must be studied as a future work.

3.4 Ice-making efficiency

In the case of no ice formation in the cooling tube, the supercooled water coming out of the tube exit flows down onto the wire net, and ice crystals with high water content are continuously formed on it. Using the flow rate of the supercooled water, Q_w (kg/min), and the net ice mass produced per minute, W (kg/min), the ice-making efficiency, η , is defined as

$$\eta = W/Q_w \times 100 \quad [\%] \quad (9)$$

The theoretical ice-making efficiency, η_{th} , is defined by Ettema et al.⁽¹¹⁾ as the ratio of the sensible heat of the supercooled water to the latent heat of solidification

$$\eta_{th} = \Delta T_s C_p / L \times 100 \quad [\%] \quad (10)$$

where $\Delta T_s (= T_f - T_{out})$ denotes the degree of supercooling based on the temperature of the water at the tube exit.

Figure 11 shows the relationship between the ice-making efficiency, η , and the degree of supercooling, ΔT_s , for three tube inner diameters. The present data indicate the results obtained for the stable region of supercooling using Eqs. (7) and (8), and those for the continuous ice making conditions observed for over four hours. The solid line in Fig. 11 shows the prediction using Eq. (10). An overall inspection of Fig. 11 reveals that the measured result increases monotonically with ΔT_s and agrees well with the prediction. This result suggests that the amount of ice formed from the supercooled water can be predicted by Eq. (10).

4. Conclusions

In order to investigate the possibility of continuous ice making using flowing supercooled water, basic experiments on the critical conditions of ice formation, stability of supercooling and the ice-making efficiency have been performed for four sets of tube dimensions under various Reynolds numbers. The conclusions are as follows

1. It has been clarified that two ice growth modes in the flowing supercooled water appear in the cooling tube according to the degree of supercooling, that is, annular ice growth mode at a low degree of supercooling and dendritic ice growth mode at a high degree of supercooling.

2. Nondimensional correlation equations of supercooling for ice formation in the laminar and turbulent flow regions have been suggested, in which the effects of flow velocity of the water, degree of supercooling and tube dimensions on ice nucleation are taken into consideration. It is also possible to distinguish between the stable and unstable regions of supercooling by using the equations.
3. It has been clarified that the ice-making efficiency in the flowing supercooled water can be predicted by Eq.(10).

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