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Fundamental research on the supercooling phenomenon on heat transfer surfaces—investigation of an effect of characteristics of surface and cooling rate on a freezing temperature of supercooled water

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Abstract—In relation to the problem of supercooling for ice storage devices, a basic investigation is carried out by performing a number of experiments and a statistical analysis. In the experiments, the freezing temperature of supercooled water on a heat transfer surface is measured. It is observed that the characteristics of the surface and the cooling condition affect the freezing temperature. The probability of the initial appearance of ice within a unit surface area in a unit time interval is introduced as a function of the degree of supercooling and the surface property. Finally, a method to predict the most probable freezing temperature of supercooled water for a given cooling condition and surface property is proposed.

1. INTRODUCTION

THERE HAS been much recent research in the area of ice forming cold energy storage. Water is usually used as a phase change material (PCM) because it is chemically stable and cheap. However, there are a few problems with the use of water as PCM. The freezing temperature of water is so low that it reduces the coefficient of performance (COP) of the refrigerator. Ice creates a thermal resistance when it forms on the heat transfer surface. A mechanical force may act on the container due to ice blockade and it restricts the ice filling ratio. When supercooling takes place, cold energy can only be stored in the form of sensible heat.

A number of researchers have been conducted in the area of supercooling. Bigg [1] handled a solidification process of a supercooled water droplet suspended by two insoluble liquid layers. He showed the correlation between the mean freezing temperature and the volume of the water droplet. He also showed the effect of the cooling rate on the mean freezing temperature qualitatively. Carte [2] suspended supercooled water droplets 9–33 μm in diameter on six different kinds of heat transfer surface, i.e. Au, Ag, Ni, silicone, stainless steel and collodion, and measured the freezing temperature of water droplets. He concluded that the lowest freezing temperature was independent of the six surfaces but depended upon the volume of the water droplets and the cooling rate.

This past research has only shown some primary factors which affect the freezing temperature, but there is no research which explains the freezing phenomenon of supercooled water quantitatively.

The purpose of this paper is to study the freezing phenomenon of supercooled water at the interface of a heat transfer surface by obtaining the correlation between the heat transfer surface property, cooling rate and freezing temperature of supercooled water. In Section 2, the freezing process on the heat transfer surface is observed visually by using a high speed camera and a video camera. The correlation between the roughness of the surface, cooling rate and freezing temperature is also investigated qualitatively. In Section 3, five kinds of heat transfer surface are prepared and a large number of experiments are carried out using each surface. From the results obtained, a quantitative conclusion is achieved. Statistical analysis is introduced and the correlation between the prob-

NOMENCLATURE

h	heat transfer coefficient at the rear side of the heat transfer surface [$\mathrm{W\,m^{-2}\,K^{-1}}$]
m	ratio of the heat transfer surface area against the standard area, $S/\Delta S$
M_i	frequency of the surface reaching the degree of supercooling of T_{i-1}
n	ratio of the time existing at the degree of supercooling in a range between T_{n-1} and T_n against the standard time, $t/\Delta t$
N_n	frequency of freezing while the degree of supercooling on the heat transfer surface is in a range between T_{n-1} and T_n
P_n	probability of ice appearing on the heat transfer surface at the degree of supercooling between T_{n-1} and T_n when the surface is cooled from 0 degrees
P_{ik}	probability of ice appearing on the heat transfer surface at the degree of supercooling between T_{i-1} and T_i when the surface is cooled from T_{i-1}
q	heat flux supplied by a heater at the rim of the heat transfer disk [$\mathrm{W\,m^{-2}}$]
S	area of the heat transfer surface [$\mathrm{m^2}$]
ΔS	standard area [$\mathrm{m^2}$]
t	time [s]
Δt	standard time [s]
t_s	total time required for freezing when the surface is cooled from 0 degrees [s]
t_n	time required to change the degree of supercooling of the heat transfer surface from T_{n-1} to T_n [s]
T	degree of supercooling [K]
T_c	refrigerant temperature [°C]
T_m	temperature within the heat transfer disk [°C]
W	probability of ice appearing on the heat transfer surface while a surface area of ΔS is kept at the degree of supercooling of T for a time interval of Δt
W_n	average value of W at the range of the degree of supercooling between T_{n-1} and T_n.

Greek symbol

α	$S/(\Delta S \Delta t)$ [$\mathrm{s^{-1}}$].

ability of freezing from the supercooling state and the freezing temperature for each kind of surface is presented.

2. OBSERVATION OF THE ICE APPEARING PROCESS

2.1. *Experimental apparatus and experimental method*

When the supercooling state of pure water terminates, dendritic ice appears suddenly on the heat transfer surface. This freezing process was observed by using a high speed camera and a video camera. The experimental apparatus is shown in Fig. 1. It consisted of five parts, namely, the test section including the cooling chamber, the cooling section to maintain the cooling medium at a constant temperature and circulate the cooling medium to the test section, the observing section to visually observe the appearance of ice on the surface, the measuring section to measure the temperature variation and the heat flux of the surface, and the refinery section to produce pure water.

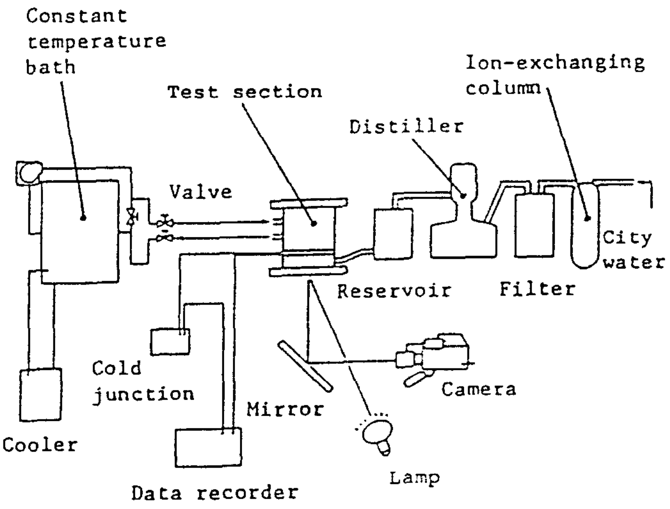


FIG. 1. Diagram of apparatus.

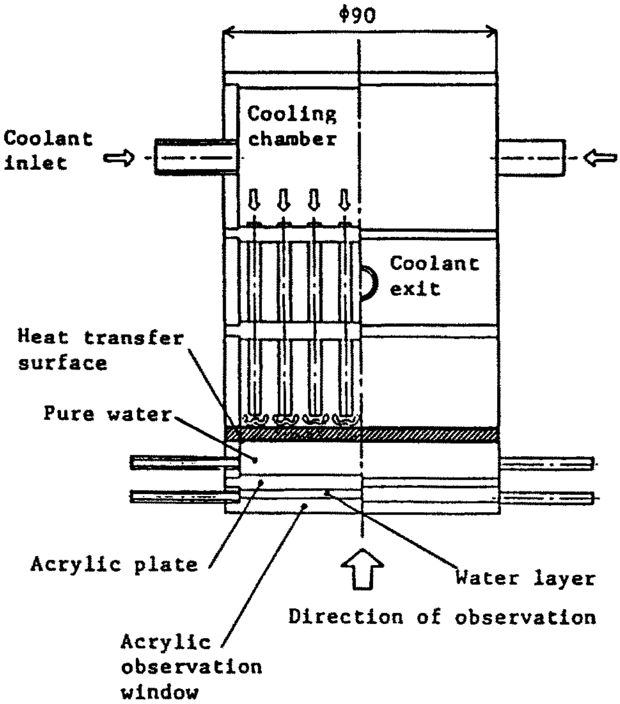


FIG. 2. Details of the test section.

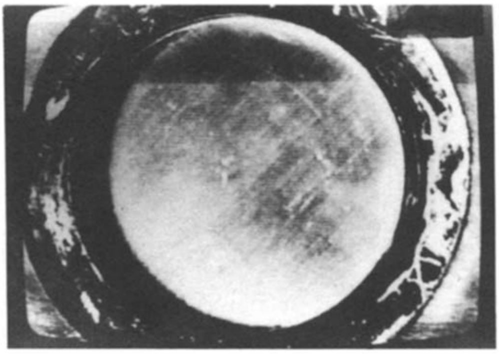
The details of the test section are shown in Fig. 2. Ethyl alcohol was used as a cooling medium and was kept at the required temperature in a constant temperature bath and transferred to a cooling chamber in the test section. It impinged against the upper surface of the heat transfer disk forming many jet flows and cooled the heat transfer surface, which was the lower surface of the heat transfer disk, uniformly. The heat transfer surface was located at the top part of the container filled with pure water and so the water was cooled downwards. The maximum density of water existed at around 4°C. Hence, a natural convection could not be induced and water could be cooled by conduction. The cooling rate was controlled by adjusting the temperature of the cooling medium but was fixed to −20°C for this series of experiments. The bottom part of the pure water container was made of a double acrylic window. The gap between the acrylic window was also filled with water so that the window surface could be kept at the temperature higher than the dew point and the ice forming process could be observed through it. Pure water was produced from city water, passed through an ion-exchanger to lower the conductivity below 10^{-6} S cm^{-1}, particles larger than 0.001 μm were removed by a filter and then distilled gently.

All the heat transfer disks used for the experiments had diameters of 90 mm but there were two types. One was to measure the surface temperature only and the other was to measure the heat flux as well. For the type 1 disk, there were two disks prepared. One was a copper disk 1 mm thick (Disk No. 1), and the other was a chrome-plated brass disk 0.8 mm thick (Disk No. 2). The type 2 disk was made of copper (refrigerant side), acrylic resin and copper (water side) having thicknesses of 3, 1 and 1 mm, respectively (Disk No. 3). The heat flux was measured using Teflon-coated Cu–Co thermocouples 0.1 mm in diameter buried in the upper and lower copper plates, and the potential difference was compared with the calibrated curve.

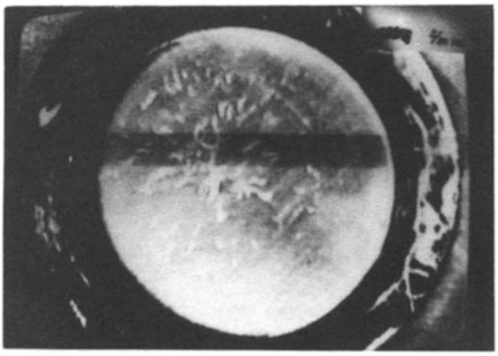
The heat transfer surface was first cleaned with ethyl alcohol and pure water, then set in the test section between the cooling chamber and the container. Next, the container was filled with pure water and the surface was cooled with refrigerant for a while until the temperature was lowered below 4°C. The surface temperature was stabilized for a while to obtain relatively uniform water temperature below 4°C. The experiment was then started by recirculating the refrigerant and cooling the heat transfer disk continuously. During the experiment, the temperature variation and heat flux variation in the heat transfer disk were measured and the ice appearing process was observed.

2.2. *Experimental results*

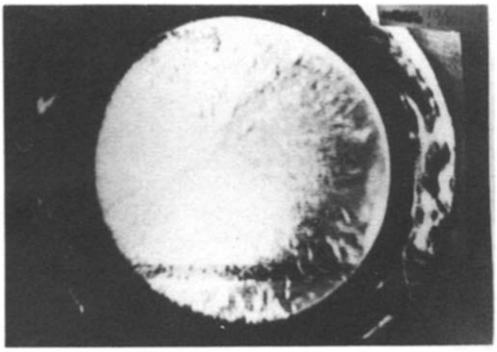
Figures 3 and 4 show one of the results obtained by using Disk No. 3 where the surface was polished in one direction using #180 sandpaper. Figures 3(a)–(c) show how the ice appears suddenly on one spot of the surface, and spreads rapidly to cover the entire surface when the pure water close to the surface is at the supercooling state. Supercooled water is essentially in an unstable condition and all the regions subjected to a supercooling state are released by the existence of the ice appearing on one spot of the surface. Figure 4 shows the time variation of the sur-



(a) $t = t_s$



(b) $t = t_s + 1/6$ s



(c) $t = t_s + 1/3$ s

FIG. 3. Ice appearing process on a copper surface.

face temperature and the heat flux. The degree of supercooling increased monotonously and after 2 min ice appeared suddenly and the degree of supercooling changed rapidly to zero. During this process, the heat flux increased once and reached a maximum, and decreased monotonously until a sudden increment was detected due to the appearance of ice. Now, concerning the time requirement for the ice to appear on the surface when the cooling process followed the curve in Fig. 4, the same results could not be obtained even from the experiments with the identical cooling process. This implied that the chance of the release from a supercooling state was subject to a statistical phenomenon. The details will be discussed in Section 3. Figure 5 shows an example of the measured surface roughness as a reference. Figures 6 and 7 show similar examples using Disk No. 2.

In order to investigate the effect of the cooling rate on the release of the supercooling state, the results using the two types of heat transfer disk were compared. One of the disks was Disk No. 3 and the other was Disk No. 1. The surfaces of both disks were polished identically, first by sand paper and then by a liquid metal polisher until the copper surfaces became mirror-like. When the temperature of the cooling medium was fixed at −20°C, the average temperature drop in a unit time interval for Disk No. 1 was much faster than for Disk No. 3. Here the cooling rate is defined as the average temperature drop in a unit time interval. The experimental results are shown in Table 1. It is clear from Table 1 that the results obtained from the two disks are distinctive, even though they have physical characteristics of the surface which are almost identical. The number of experiments given in this table was not large enough for us to discuss the effect of the cooling rate quantitatively, but a tendency of lower freezing temperature for the experiments under a higher cooling rate was clearly observed. We believe that the reason for this tendency is the change of the probability of the appearance of ice resulting from the reduction of the time required to pass through each degree of supercooling.

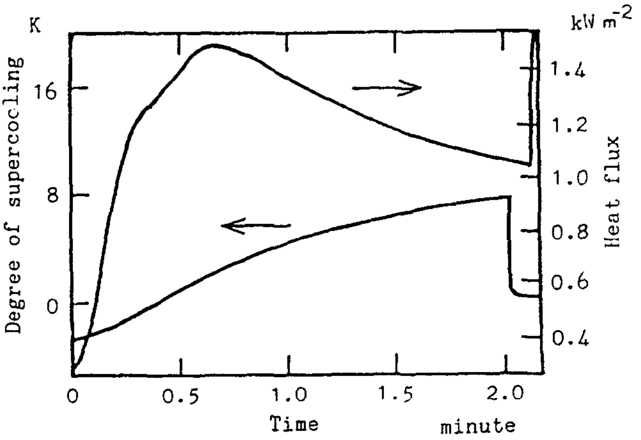


FIG. 4. Temperature and heat flux variation of Disk No. 3.

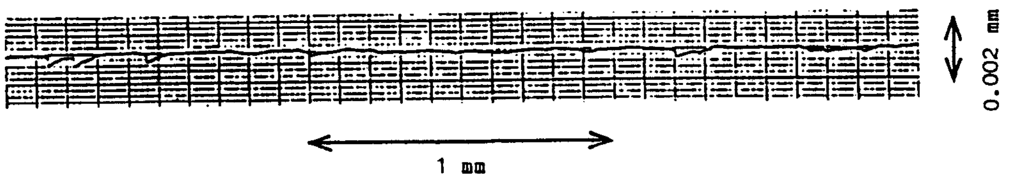
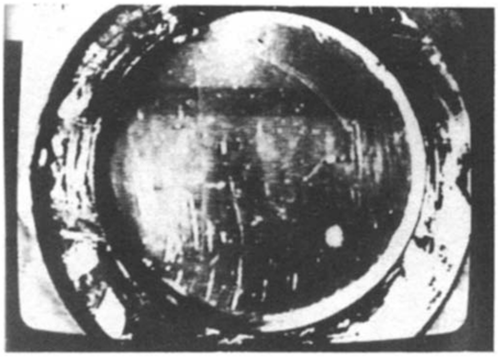
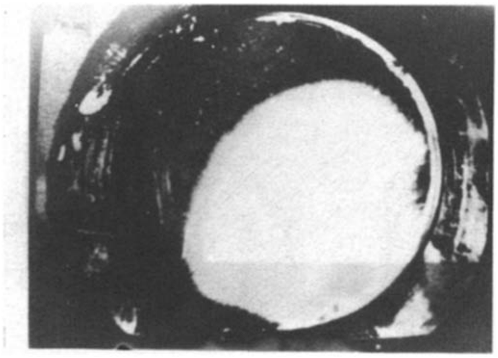


FIG. 5. Surface roughness of Disk No. 3.

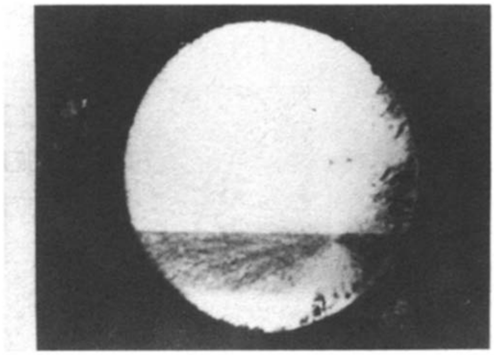
In order to investigate the effect of the surface roughness on the release of the supercooling state, the chrome-plated brass surface (Disk No. 2) whose measured roughness was as shown in Fig. 8 was used and one small portion on the surface was scratched using sand paper #400. The location of the initial appearance of ice was observed. Figure 9 shows one of the results obtained using a high speed camera and it shows that the location of the initial appearance of ice was at the scratched part and that it spreads rapidly to cover the entire surface. This result was obtained repeatedly. The time variation of the surface temperature corresponding to the experiment in Fig. 9 is shown in Fig. 10 as a reference.



(a) $t = t_s$



(b) $t = t_s + 1/6$ s



(c) $t = t_s + 1/3$ s

FIG. 6. Ice appearing process on a chrome-plated brass surface.

3. STATISTICAL INVESTIGATION OF THE FREEZING TEMPERATURE

In the last section, it was pointed out that the degree of supercooling at the moment the ice appeared on the surface should not necessarily be the same even if the identical cooling process is followed. In this section, a number of experiments are carried out using various kinds of surfaces, and the frequency distribution showing the degree of supercooling at the moment the ice appeared is presented. From a statistical point of view, a method to calculate the probability of the appearance of ice is introduced and the probability for each surface is presented.

3.1. *Experimental apparatus*

The details of the experimental apparatus including the test section were basically the same as in Section 2.1 except for the type of surfaces used. Copper disks were used as heat transfer disks and the surfaces were treated in the following five ways: (A) electrolytically polished, (B) buffed, (C) gold-plated, (D) nickel-plated and (E) porous. The porous copper surface was made by sintering, having a void fraction of 20%. Two kinds of porous copper surface were prepared,

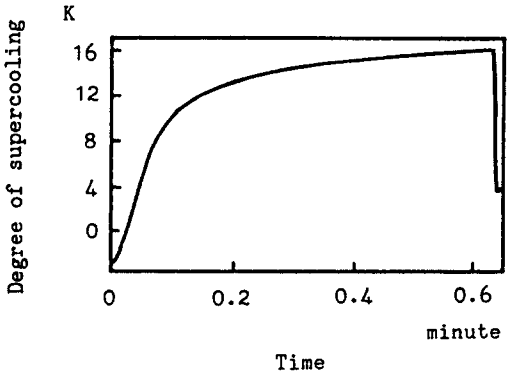


FIG. 7. Temperature variation of Disk No. 2.

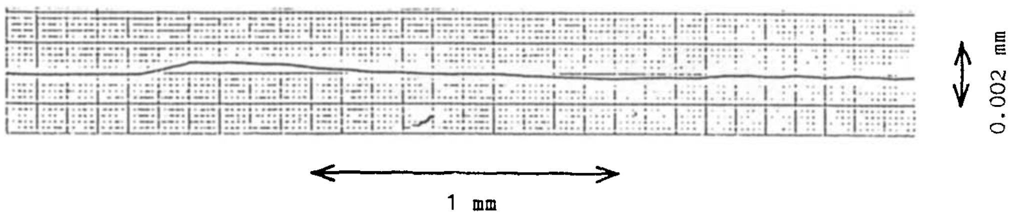


FIG. 8. Surface roughness of Disk No. 2.

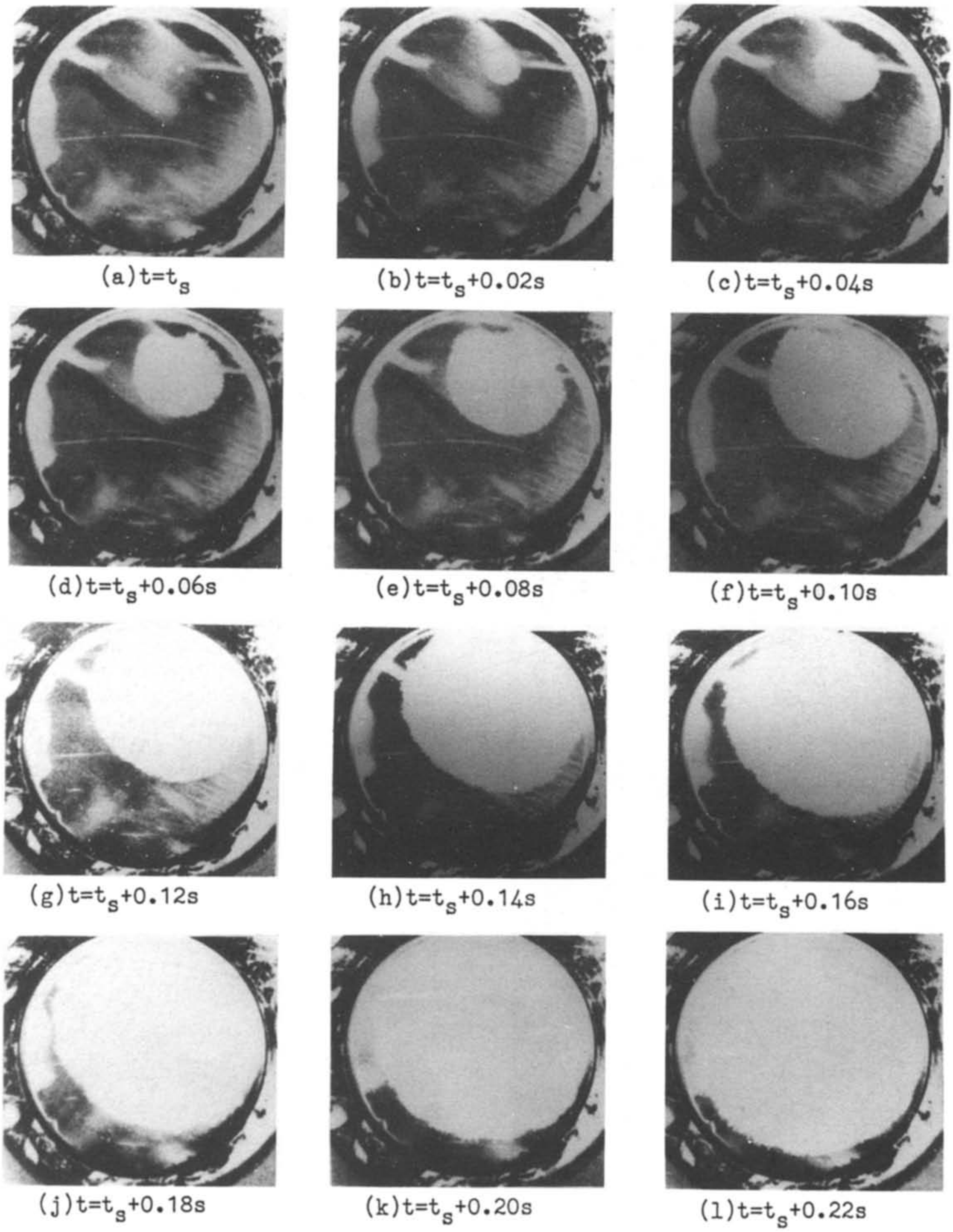

(a) $t=t_s$
(b) $t=t_s+0.02s$
(c) $t=t_s+0.04s$
(d) $t=t_s+0.06s$
(e) $t=t_s+0.08s$
(f) $t=t_s+0.10s$
(g) $t=t_s+0.12s$
(h) $t=t_s+0.14s$
(i) $t=t_s+0.16s$
(j) $t=t_s+0.18s$
(k) $t=t_s+0.20s$
(l) $t=t_s+0.22s$

FIG. 9. Ice appearing process on a chrome-plated brass surface partially scratched.

Table 1. Experimental results of the mean freezing temperature of supercooled water under two different cooling conditions

	Temperature range of freezing (°C)	Mean freezing temperature of supercooled water (°C)	Standard deviation
Surface I	−11.9 to −13.4	−12.9	0.86
Surface III	−8.9 to −6.9	−7.7	0.64

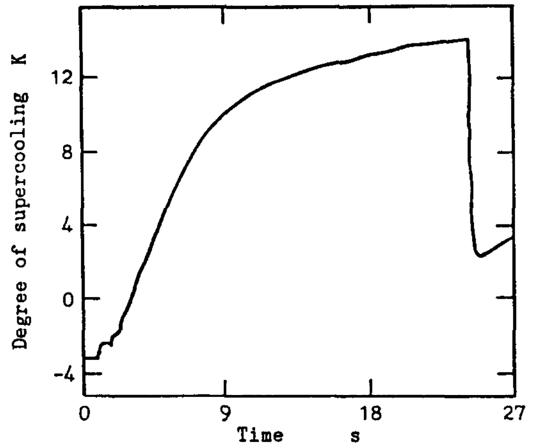
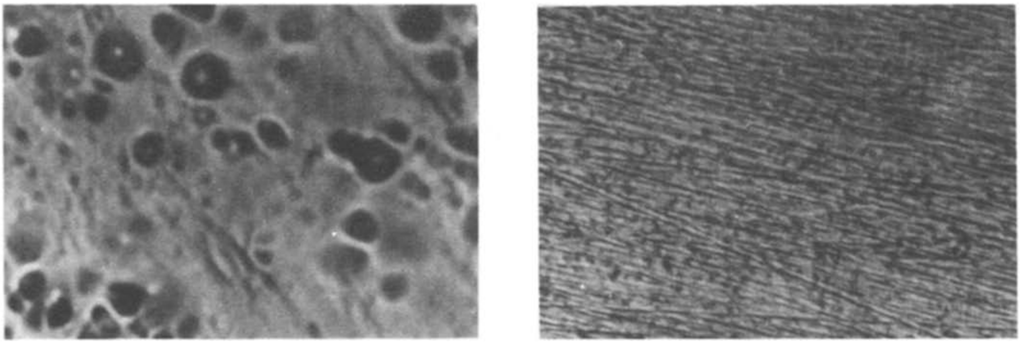


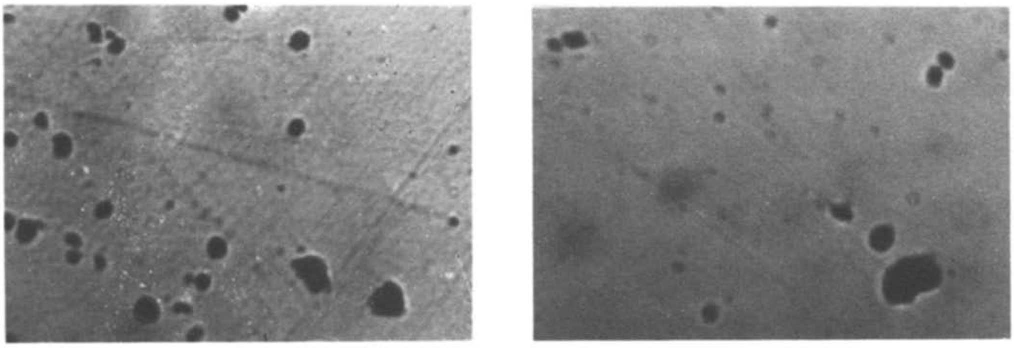
FIG. 10. Temperature variation of Disk No. 2 partially scratched.

one 3 mm thick and the other 6 mm thick. Surface (A) was made by placing the surface under a current density of 0.46–0.48 A cm^{-2} for 150 s in an electrolytic solution whose composition was H_3PO_4, Cr_2O_3 and H_2O, having a weight fraction of 74, 6 and 20%, respectively. In order to prevent performing the experiments without recognizing a lack of uniformity, two identical surfaces were prepared for each kind of surface. Figure 11 shows microphotographs of the surfaces (A)–(D). It shows that the gold-plated and the nickel-plated surfaces (C) and (D) were relatively smooth, whereas the buffed surface (B) had very thin scratches in one direction and the electrolytically polished surface (a) was relatively rough. Figure 12 shows the measured results of the surface roughness using a tracer method.

The details of the heat transfer disk are shown in

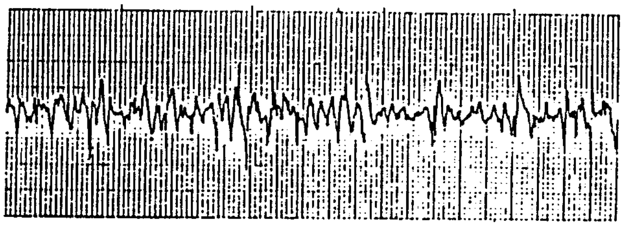


(a)Electrolytically polished (b)Buffed

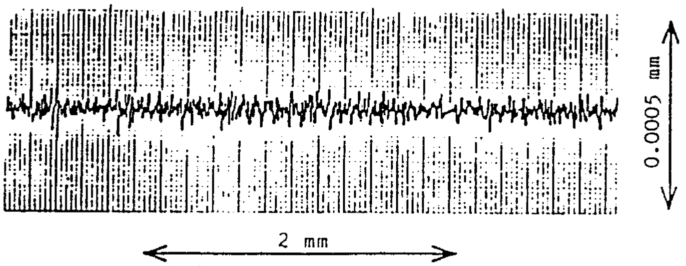


(c)Gold-plated (d)Nickel-plated

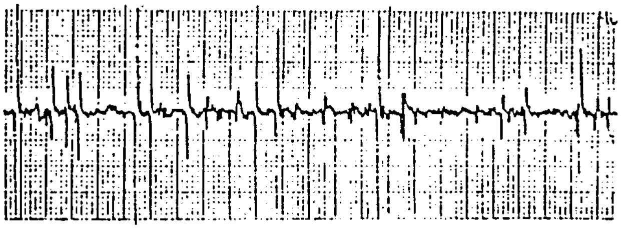
FIG. 11. Microphotography indicating the heat transfer surfaces.



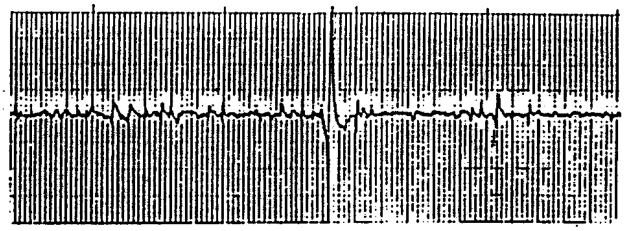
(A) Electrolytically polished surface



(B) Buffed surface



(C) Gold-plated surface



(D) Nickel-plated surface

FIG. 12. Surface roughness of the various heat transfer surfaces.

Fig. 13. There was a tendency of observing the initial ice appearance at the interface between the pure water container and the heat transfer disk, if they were simply joined together and cooled. In order to prevent such an effect, a circular gap, 4 mm deep and 6 mm wide, was cut out along the fringe of the copper disk, 90 mm diameter and 5 mm thick, and filled with a low conductive material. By warming the circumference using a heater during the experiment, the disk temperature inside the gap was kept almost uniform while the temperature outside was comparatively higher. One of the analytical results describing the temperature distribution inside the disk is shown in Section 3.5. Seven pairs of thermocouples were placed along the two radial directions at the location shown

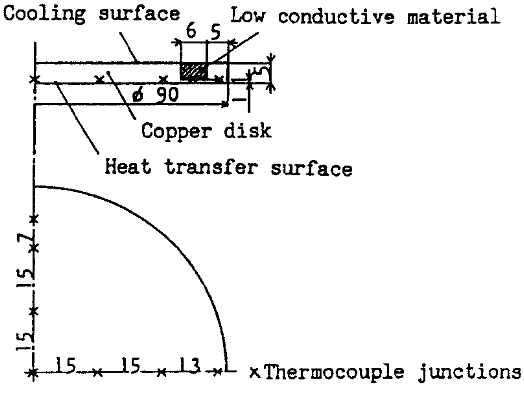


FIG. 13. Details of the heat transfer disks.

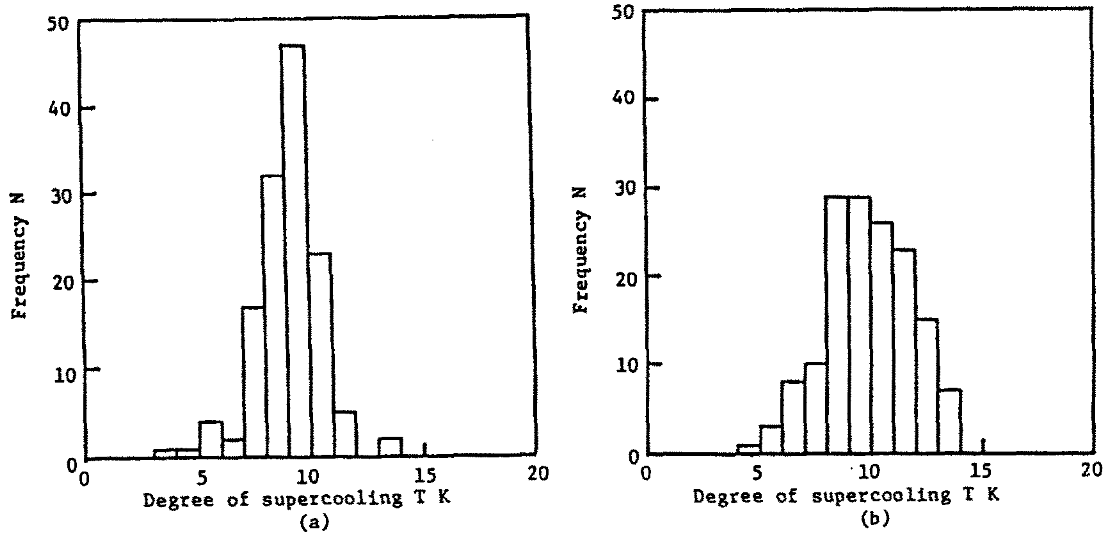


FIG. 14. Frequency of the initial ice appearing on the electrolytically polished copper surfaces (A-a) and (A-b).

in Fig. 13. The thermal resistance between the surface and water could be considered as negligible, and hence the measured temperature could be taken as the water temperature in contact with the surface.

3.2. *Experimental method*

The heat transfer surface was cleaned with ethyl alcohol and pure water before it was set in the test section. As was described in Section 2.1, the container beneath the heat transfer surface was filled with pure water and cooled for a while to obtain a water temperature below 4°C. By stabilizing the temperature of the disk for a while, the temperature of the water inside the container became uniform. The experiment was then started by circulating the cooling medium and the temperature variation of the surface was measured and the location where the initial ice appeared was observed.

3.3. *Experimental results*

A number of experiments were carried out using five kinds of surfaces under cooling rates ranging between 0.2 and 0.5 K s^{-1}, and the degree of supercooling at the moment the ice appeared was measured. Frequency distributions of the ice appearance at each degree of supercooling for the electrolytically polished copper surfaces (A-a) and (A-b) are shown in Fig. 14 and the locations of the appearance are shown in Fig. 15. From these results, the surface could be considered fairly even and both surfaces could be taken as similar. There was no particular location where the ice appeared more than the other parts but was distributed evenly throughout the surface. A summary of the experimental results for each kind of surface is shown in Table 2. Ice appeared at a lower degree of supercooling on relatively rough surfaces such as the electrolytically polished surface (A) or the porous sur-

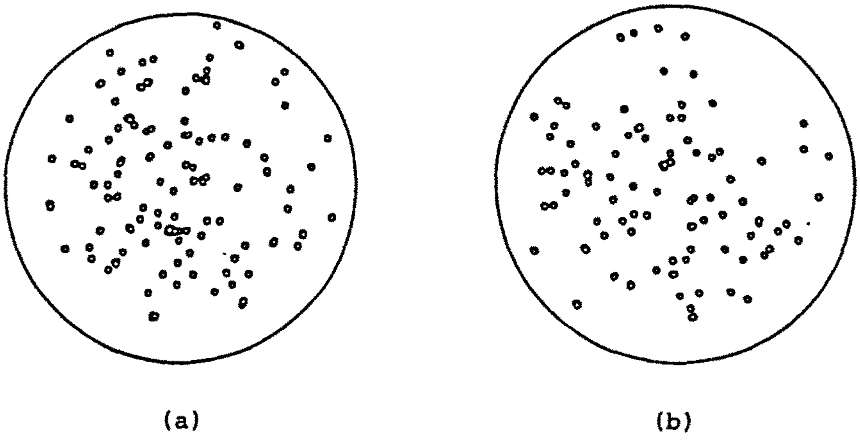

(a) (b)

FIG. 15. Location of the ice appearance on the electrolytically polished copper surfaces (A-a) and (A-b).

Table 2. Experimental results on the mean degree of supercooling for various kinds of surfaces

Type of surface	No. of measurements	Mean degree of supercooling (K)
(A) Electrolytically polished	285	9.5
(B) Buffed	127	13.8
(C) Gold-plated	149	13.4
(D) Nickel-plated	55	11.7
(E1) Porous	129	7.8
(E2) Porous	99	7.4

face (E) compared with the results obtained using relatively smooth surfaces such as the buffed surface (B). This implies that the degree of supercooling at the moment the ice appeared was effected by the surface roughness and thus the supercooling state can be minimized by applying a certain roughness on the surface. As far as the results for the porous surface are concerned, having the actual surface area larger than the others may also be the reason for getting a lower mean degree of supercooling.

3.4. *Statistical analysis*

It was clarified from the experimental results that the releasing ability from a supercooling state was very much related to the characteristics of the surface. On a macroscopically uniform surface such as the surface used for these experiments, ice did not appear at a particular location on the surface but the location was distributed evenly throughout the whole surface. Once the ice appeared on one spot, it spread rapidly to cover the entire surface. By investigating the location of the appearance of ice microscopically, ice appearing from a particular spot having a certain surface condition might be observed frequently compared with the other spots. However, by considering a unit surface as a surface having a sufficiently large quantity of such particular spots, the releasing ability of the surface consisted of such unit surfaces that could be taken as uniform, not relating to any particular location but relating to the degree of supercooling and the average characteristics of the surface.

From this point of view, let $W(T)$ $(0 \leqslant W \leqslant 1)$ be the probability that supercooled water is frozen when it is exposed to a heat transfer surface having a degree of supercooling T and an area ΔS for a time interval of Δt. Naturally, the probability of ice not appearing on the surface for a time interval of Δt becomes $1-W(T)$. Therefore, the probability of ice not appearing on the surface having a surface area $m\Delta S$ kept at the degree of supercooling T for a time interval of $n\Delta t$ can be expressed as

$$(1-W(T))^{mn} \tag{1}$$

and the probability of freezing at the next time interval, i.e. $(n+1)\Delta t$, can be expressed as

$$(1-W(T))^{mn}[1-(1-W(T))^{m}]. \tag{2}$$

Considering the case where a heat transfer surface follows the cooling process shown in Fig. 16, the probability of ice appearing at the degree of supercooling between T_{n-1} and T_n when the surface is cooled from

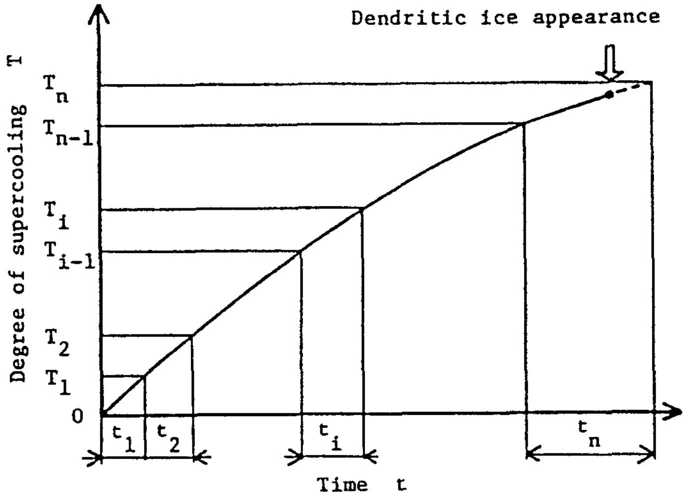


FIG. 16. Time dependency of the degree of supercooling.

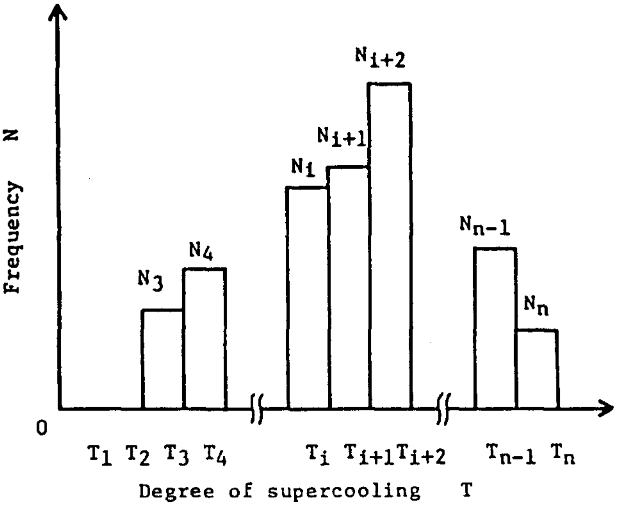


FIG. 17. Frequency distribution of the degree of supercooling.

0 degrees can be expressed as

$$P_n = (1-W_1)^{t_1\alpha}(1-W_2)^{t_2\alpha}\cdots[1-(1-W_n)^{t_n\alpha}] \quad (3)$$

where $\alpha = S/(\Delta S \Delta t)$. t_n is defined as the time required for the passage through the degree of supercooling between T_{n-1} and T_n, and W_n is defined as the average value of $W(T)$ for that temperature range. Based on this idea, the degree of supercooling at the moment of appearance of ice need not be one particular value even if the surface follows an identical cooling process, but should be distributed statistically around a certain average value. This behaviour agrees with the experimental results observed in this paper.

Next, the meaning of the frequency distribution obtained in the last section is considered below. Figure 14 shows the frequency distributions obtained using the electrolytically polished surfaces as one of the examples. The cooling process for each experiment should not necessarily be the same. Figure 17 shows a model of the frequency distribution. The number of experiments cooled from 0 degrees are $(N_3+N_4+\cdots+N_n)$, but ice appeared before the surface reached T_{i-1} on $(N_3+N_4+\cdots+N_{i-1})$ experiments. The number of experiments experiencing the degree of supercooling T_{i-1} was $M_i = (N_i+N_{i+1}+N_{i+2}+\cdots+N_n)$. Out of M_i experiments, let the probability of the appearance of ice at the degree of supercooling between T_{i-1} and T_i when the surface is cooled from T_{i-1} be P_{ik}. Then P_{ik} can be expressed as

$$P_{ik} = 1-(1-W_i)^{t_{ik}\alpha} \quad (4)$$

where t_{ik} is the time required for the surface to pass through the degree of supercooling between T_{i-1} and T_i for the kth experiment. The symbol k is the numbering of each experiment and it lies between 1 and $(N_i+N_{i+1}+N_{i+2}+\cdots+N_n)$.

Therefore, if a large number of experiments are carried out, the following relationship can be established:

$$N_i = \sum_{k=1}^{M_i}[1-(1-W_i)^{t_{ik}\alpha}] \quad (5)$$

where $M_i = N_i+N_{i+1}+\cdots+N_n$.

The five kinds of heat transfer surface used in these experiments had their own specific value of $W(T)$ and the experimental results obtained for each surface can be considered as the value indicated in equation (5). W was set to zero at $T = 0$ K and set to 1 at $T = 273$ K. Using the value obtained from the series of experiments, the probability W_i for each kind of surface was calculated using equation (5). Figure 18 shows the relationship between the probability of ice appearance W and the degree of supercooling T for each kind of surface, based on a unit surface area $\Delta S = 6.36\times10^{-3}$ m^2 and a unit time interval $\Delta t =$

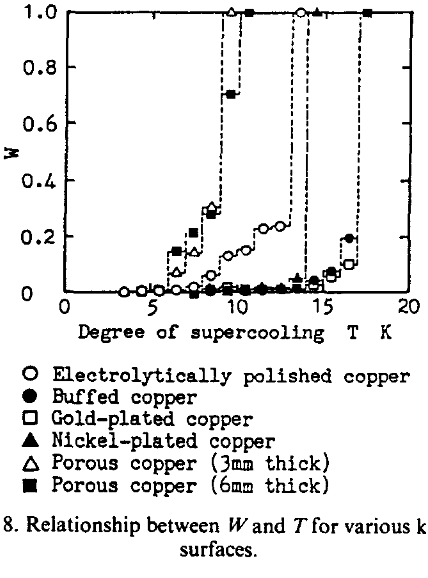


FIG. 18. Relationship between W and T for various kinds of surfaces.

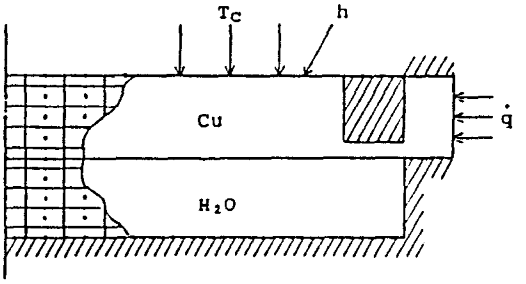


FIG. 19. Calculation model for temperature distribution of the heat transfer disk.

1 s. It indicates that the characteristics of the surface influence the freezing temperature of the supercooled water greatly.

Hence, by applying this method, the relationship between the probability W and the degree of supercooling T for various kinds of surfaces can be obtained experimentally in advance, and values such as the most probable degree of supercooling at the moment the ice appeared and the probability of the appearance of ice for each degree of supercooling, can be predicted for given surface characteristics, surface area and cooling conditions.

The number of experiments carried out in this paper was 50–300. For a higher degree of supercooling, the number of experiments reaching that degree of supercooling naturally became less and led to the possibility of errors being included in the calculated value W at that degree of supercooling. However, the number of experiments carried out here was still large enough to investigate the effect of the surface characteristics.

3.5. *Discussion on the temperature distribution in the heat transfer disk*

In order to investigate the effect of the circular gap along the fringe of the disk, the non-steady state temperature distribution in the disk was calculated analytically. The model used for this calculation is shown in Fig. 19. The size was taken to be identical to the real heat transfer disk shown in Fig. 13. Figure 20 shows one of the examples presenting isothermal lines. According to the results obtained, a relatively uniform temperature distribution within the gap was established, having a temperature difference less than 0.5°C, while the temperature outside the gap was 3–5°C higher than the temperature inside. Similar results were also obtained by the experimental measurements.

Furthermore, it was not necessary to consider the temperature distribution on the surface for the cooling condition used in this paper, but for the experiments

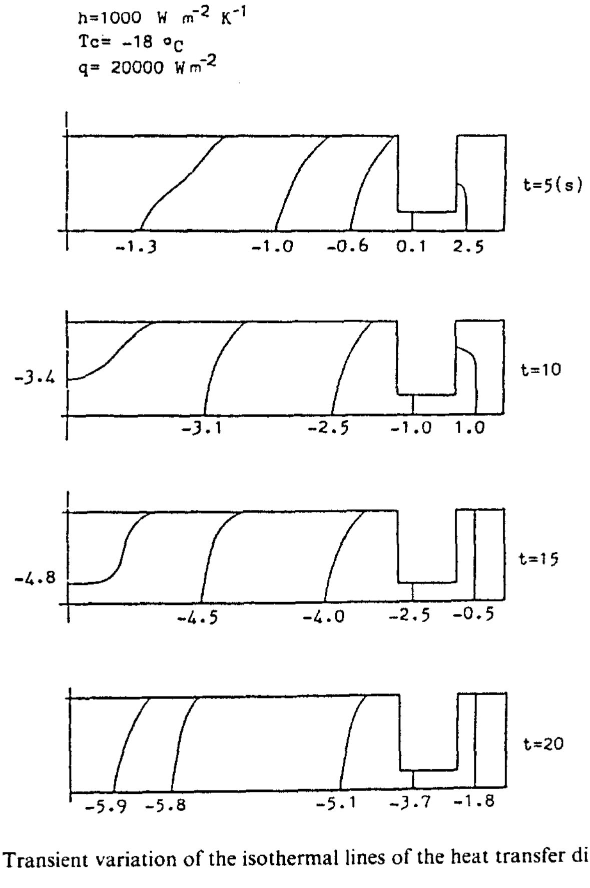


FIG. 20. Transient variation of the isothermal lines of the heat transfer disk (T_m).

under a higher cooling rate, it would be hard to obtain a uniform temperature distribution on the surface. Therefore the method for calculating the probability $W(T)$ introduced here cannot be applied directly to the case. However, even for such a case, a similar analysis can be applied by dividing the surface imaginary and treating the probability of the surface as a combination of the probabilities for each divided section.

4. CONCLUSION

In relation to the supercooling problem in ice storage devices, the freezing process of supercooled water was investigated. It was found from the experiments using a high speed camera that the cooling rate and the surface characteristics such as roughness influenced the freezing temperature of supercooled water. Furthermore, in order to discuss such effects quantitatively, a large number of experiments were carried out on five kinds of heat transfer surface and the frequency distribution of the freezing temperature for each surface was obtained. Based on the statistical phenomenon of the freezing temperature of supercooled water, an analytical method was introduced and the relationship between the probability of the appearance of ice and the degree of supercooling for each kind of surface was shown. Finally, a method to predict the most probable freezing temperature for given surface characteristics, surface area and cooling conditions was presented.

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RECHERCHE FONDAMENTALE SUR LE PHENOMENE DE SURREFROIDISSEMENT AUX SURFACES DE TRANSFERT THERMIQUE—ETUDE DE L'EFFET DES CARACTERISTIQUES DE SURFACE ET DE LA VITESSE DE REFROIDISSEMENT SUR LA TEMPERATURE DE CONGELATION DE L'EAU SURREFROIDIE

Résumé—Liée au problème du surrefroidissement dans les unités de stockage de glace, une étude fondamentale est faite à travers plusieurs expériences et une analyse statistique. Dans les expériences, on mesure la température de congélation de l'eau surrefroidie à la surface froide. On constate que les caractéristiques de la surface et la condition de refroidissement agissent sur cette température. La probabilité d'apparition initiale de la glace par unité de surface et par unité de temps est introduite comme étant une fonction du degré de surrefroidissement et des propriétés de la surface. Une méthode est proposée pour la prédiction de la température de congélation la plus probable d'eau surrefroidie, pour des conditions données de refroidissement et de propriétés de surface.

GRUNDLEGENDE ERFORSCHUNG DER UNTERKÜHLUNG VON WÄRMEÜBERTRAGENDEN OBERFLÄCHEN—UNTERSUCHUNG DER EINFLÜSSE VON OBERFLÄCHENCHARAKTERISTIK UND ABKÜHLUNGSGESCHWINDIGKEIT AUF DIE ERSTARRUNGSTEMPERATUR VON UNTERKÜHLTEM WASSER

Zusammenfassung—In dieser Arbeit wird über eine Anzahl von Versuchen und eine statistische Auswertung berichtet, um das Problem der Unterkühlung bei Eisspeicherbehältern grundlegend zu untersuchen. Bei diesen Experimenten wird die Erstarrungstemperatur des unterkühlten Wassers an der Kühlfläche gemessen. Es wird beobachtet, daß die Oberflächeneigenschaften und die Kühlbedingungen Einfluß auf die Erstarrungstemperaturen haben. Die Wahrscheinlichkeit der Eisentstehung auf einer Flächeneinheit in einer Zeiteinheit wird in Abhängigkeit vom Unterkühlungsgrad und von der Oberflächeneigenschaft dargestellt. Schließlich wird ein Verfahren vorgestellt, um die wahrscheinlichste Erstarrungstemperatur von unterkühltem Wasser bei gegebener Kühlbedingung und Oberfläche zu berechnen.

ФУНДАМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ ЯВЛЕНИЯ ПЕРЕОХЛАЖДЕНИЯ НА ПОВЕРХНОСТЯХ ТЕПЛОПЕРЕНОСА—ИЗУЧЕНИЕ ВЛИЯНИЯ ХАРАКТЕРИСТИК ПОВЕРХНОСТИ И СКОРОСТИ ОХЛАЖДЕНИЯ НА ТЕМПЕРАТУРУ ЗАМОРАЖИВАНИЯ ПЕРЕОХЛАЖДЕННОЙ ВОДЫ

Аннотация—Методом статистического анализа экспериментальных данных проведено фундаментальное исследование переохлаждения применительно к устройству для получения льда. Измерена температура замораживания переохлажденной воды на поверхности теплопереноса. Показано, что на температуру замораживания влияют характеристики поверхности и условия охлаждения. Введена вероятность первоначального появления льда на единице площади поверхности за единицу времени как функция степени переохлаждения и свойств поверхности. Предложен метод определения наиболее вероятной температуры замораживания переохлажденной воды при заданных условиях охлаждения и свойствах поверхности.