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Fundamental research on external factors affecting the freezing of supercooled water

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Abstract—In relation to the problem of supercooling for ice storage devices, various kinds of experiments were carried out to find some factors which control the supercooling phenomenon. The following were selected as the external factors: rubbing glass with glass in water, collision of a solid in water, convection generated by rotating a solid in water, a jet stream, vibration and shock. It was found that factors such as convection, vibration and non-contacting shock have no effect on the freezing of supercooled water. They seem to be just adding some positive energy to water. On the other hand, collision or rubbing between solids or between a solid and a liquid surface in supercooled water helps the water to freeze. We believe that the growth of the ice embryo is induced by making the water molecules closer to each other, whose motion was restricted by a solid or liquid surface.

1. INTRODUCTION

IN ORDER to overcome a relatively high electrical load during the day time, especially due to the heavy consumption of air conditioning, improvement of the efficiency of ice forming cold energy storage system using midnight power is increasing in importance. However, the existence of supercooling at the initial stage of ice forming reduces the heat flux through a heat transfer surface significantly. It causes a reduction in the ice forming rate at the same time. There may be even the case that no freezing takes place and cold energy can only be stored as the sensible heat. On the other hand, the ice layer formed on the heat transfer surface becomes thermally resistant, which reduces the coefficient of performance of the refrigerator. In such a case, one of the solutions to improve the efficiency is to remove the supercooled water away from the surface without freezing it, keeping the surface always in contact with water, and then to freeze it in another ice storage container. Therefore, this is one of the important themes used to clarify the phase change phenomenon from supercooled water to ice, and to find some method to control it.

There are many works concerning supercooling, but very few of them deal with external factors needed to induce or suppress the freezing of supercooled water. Hence, there may be still many unknown factors to discover.

Kashiwagi *et al.* [1] carried out experiments using enclosed rectangular containers of various heights. They performed two kinds of experiments, one was to cool from the top and the other was to cool from the bottom, and by comparing the results, they discussed the effect of natural convection on the freezing of supercooled water. They concluded that the turbulence induced by the bulk convective flow influences the freezing of supercooled water. However, the difference in the average degree of supercooling at freezing due to the existence of convection was only 1 or 2 K. Therefore, from the point of view of controlling the supercooled water, it is not suitable to include it as one of the external factors.

Nagashima *et al.* [2] carried out experiments of shaking a glass container vertically which contained a large volume of supercooled water inside. They also carried out experiments of cooling water, rotated by a stirrer, under a constant cooling rate. They examined the effect of vibration and stirring on the freezing of supercooled water by comparing them with the results under no external factors. They reported that by applying such an external factor at more than a certain level, the effect appeared significant. It was concluded that the reason for this effectiveness was cavitation. However, exposing the liquid surface to an atmosphere could also be one of the possible reasons for it.

Johannsen [3] applied 1 MHz vibration to water for 30 s, and reported that there was a drastic change in the characteristics of the water. The water could be

NOMENCLATURE

h	falling height of a steel ball [mm]	T_{ave}	average degree of supercooling at freezing [K].
t	time [ms]		

maintained at a relatively high degree of supercooling and the behavior remained for more than 2 months without adding another vibration.

Thus, in order to control the phase change, it is necessary to carry out a further investigation concerning the relationships between the freezing of supercooled water and the various kinds of external factors.

In this report, experiments of applying various kinds of external factors to supercooled water having a certain volume under a constant cooling rate are carried out. From the experimental results, the effectiveness of each factor to the freezing of supercooled water is investigated. The effect of rubbing glass with glass in supercooled water, and the effect of collision of glass against glass in supercooled water are investigated in Sections 2 and 3, respectively. In Section 4, the effect of forced convection by rotating a solid in supercooled water and by applying a jet stream in supercooled water is investigated. In Section 5, external factors are examined by applying continuous vibration to an enclosure containing supercooled water and by applying continuous vibration to a solid in supercooled water. In Section 6, the effect of applying shock by hitting the outer surface of a water container and the effect of applying shock to a bar whose tip was dipped in supercooled water are investigated.

2. EFFECT OF RUBBING SOLID AGAINST SOLID IN SUPERCOOLED WATER

2.1. *Experimental apparatus and experimental method*

The experimental apparatus to rub the tip of the glass bar against the bottom of the test tube containing the test water is shown in Fig. 1(a). The test tube was made of glass. The glass bar was also made of a glass tube, closed at the tip and fitted with a thermocouple inside. The glass bar oscillates horizontally by means of an oscillator. Ethylene glycol was used as a coolant and its temperature was controlled in a cold bath by a refrigerator, an immersion cooler, a heater and the addition of liquid nitrogen. The coolant was supplied to the test section and around the tube and circulated back to the cold bath. The cooling rate was set to 0.25 ± 0.02 K min^{-1}. The top of the test water contained in the test tube was closed by an oil layer, to separate the supercooled water from the atmosphere and from the frosted glass wall. Otherwise, frost may come into existence in the air and may enter into the test water to become an ice embryo. During the experiments, the frequency, the amplitude and the cooling rate were fixed until freezing took place. The frequency and the amplitude at the tip were measured using another apparatus, as shown in Fig. 1(b). A test tube was cut very short, so that a gap sensor was set very near to the tip of the glass bar to measure the behavior of the tip under the same conditions.

The test water used in this report was producd by the following process. City water was passed through an ion-exchanger to lower the conductivity below 10^{-6} S cm^{-1} and particles larger than 0.001 μm were removed by a filter and then gently distilled.

2.2. *Experimental results*

Figure 2 shows the experimental results. It can be observed that there is a tendency for the average

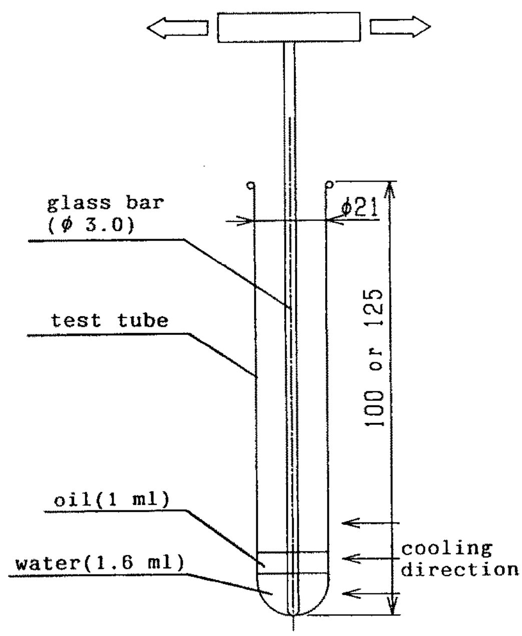


FIG. 1(a). Experimental apparatus for rubbing glass with glass.

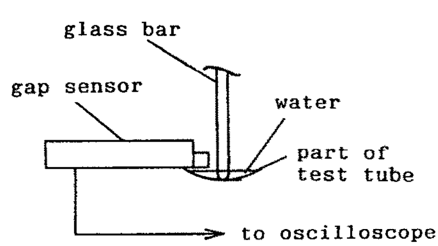


FIG. 1(b). Experimental apparatus to measure the movement of a glass bar.

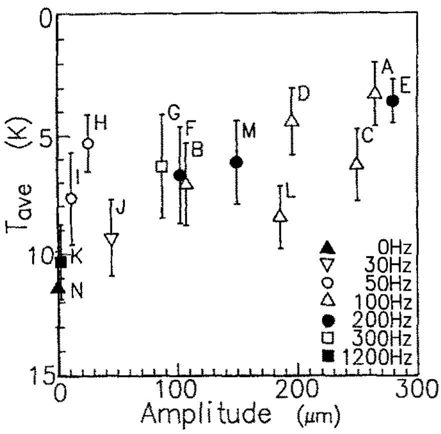
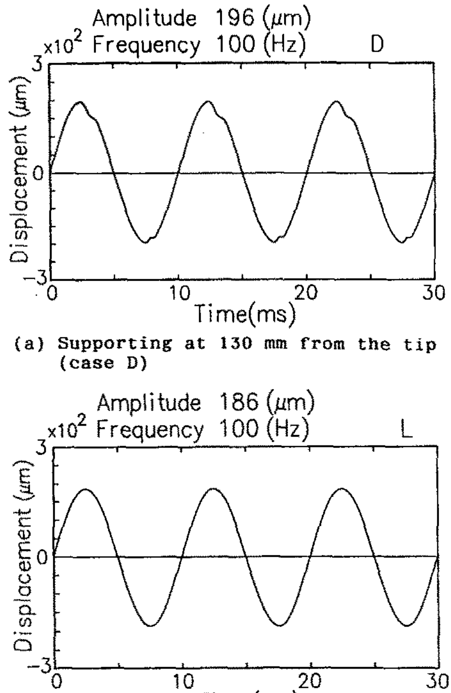


FIG. 2. Average degree of supercooling at freezing (rubbing glass with glass).

degree of supercooling at freezing to decrease as the amplitude increases. The initial ice always appeared at the contacting point. Therefore, it was confirmed that rubbing glass with glass in supercooled water influences the freezing phenomenon of supercooled water. In the case of experiments under a low frequency, such as 30 or 50 Hz, the degree of supercooling at freezing varied quite widely. Especially in the case of 50 Hz, a sudden decrease of the degree of supercooling at freezing can be observed with increasing amplitude. However, by examining the tip motion in the 50 Hz case, it was found that the motion was unsteady. Therefore, this kind of unsteady motion can be considered as another external factor influencing the freezing phenomenon of supercooled water.

Figure 3 shows the results obtained under a frequency of 100 Hz. The groups A, B and D are the results obtained by supporting the glass bar at a position 130 mm above the tip, and groups C and L at 105 mm, and continuous oscillation applied to rub the glass bar against the bottom of the test tube. There is a distinct difference in the results. In order to find



(a) Supporting at 130 mm from the tip (case D)

(b) Supporting at 105 mm from the tip (case L)

FIG. 4. Displacement of the tip of a glass bar.

the reason for this difference, the displacement of the tip of the glass bar for groups D and L is compared in Figs. 4(a) and (b), as their frequencies and amplitudes were very close to each other. The wave form in the case of group L is smooth, but some distortion near the top and the bottom of the wave form can be observed in the case of group D. Therefore, it can be said that such distortion in wave form increases the ability of freezing further.

A relatively smooth wave form for supporting at the position 130 mm was achieved under a constant frequency of 200 Hz, and the results are shown in Fig. 5. The glass bar was supported at 105 mm for group

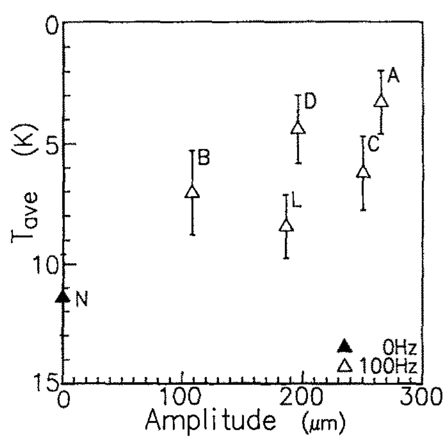


FIG. 3. Average degree of supercooling at freezing (rubbing glass with glass at 100 Hz).

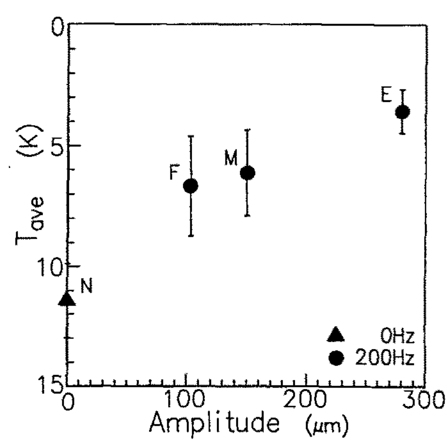


FIG. 5. Average degree of supercooling at freezing (rubbing glass with glass at 200 Hz).

M, and 130 mm for the others. A consistent tendency can be observed without any relationship with the supporting position. Therefore, it can be concluded that if the wave form of the tip of rubbing glass is relatively smooth, increasing the frequency or the amplitude of rubbing glass with glass increases the ability of freezing.

3. EFFECT OF COLLISION OF SOLIDS IN SUPERCOOLED WATER

3.1. *Experimental apparatus and experimental method*

The experimental apparatus to investigate the effect of collision is shown in Fig. 6. The tip of a glass bar, 4 mm in diameter, collides onto the bottom of a test tube containing the test water. The cooling method and the cooling rate are the same as in Section 2. The falling speed was controlled using a reversible motor, and the level of collision was evaluated by measuring the maximum vertical displacement at the bottom of the test tube from the outside. There were some cases where the level of collision was too low to be measured. Therefore, a plate made of bakelite having a thickness of 0.5 mm was used to measure the level of collision in such a case, and estimated to the equivalent value for the test tube. The motor was stopped immediately after the collision. The glass bar was not fixed firmly to the supporting part to prevent it from colliding twice or rubbing against the bottom. After the collision, the glass bar was lifted up very slowly to prepare for the next fall. During the experiment,

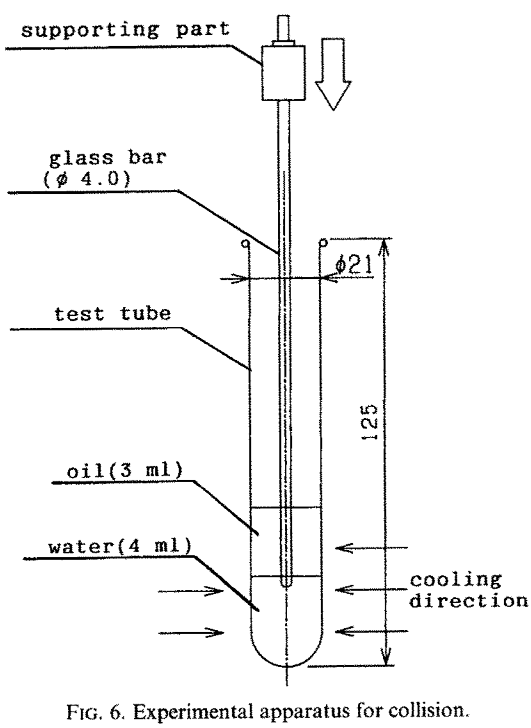


FIG. 6. Experimental apparatus for collision.

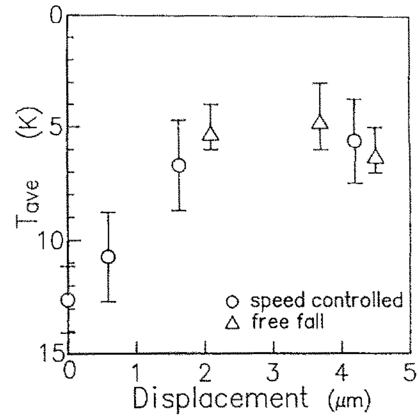


FIG. 7. Average degree of supercooling at freezing (collision).

the collision was carried out twice at each degree of supercooling until freezing took place.

3.2. *Experimental results*

The experimental results by making a glass bar collide with the bottom of the test tube are shown in Fig. 7 in the form of an average degree of supercooling at freezing against the maximum displacement at the bottom. The initial ice always appeared at the tip of the glass bar at the instant of collision. The results obtained by using a speed adjustable motor are the average value out of around 50 runs of the experiments. The results obtained by free fall from the heights 1, 3 and 5 mm are also shown in the figure for reference. The number of experiments for each free fall condition was around 5, but still a consistent tendency can be observed. Therefore, it can be concluded that collision of glass against glass in supercooled water is effective, and it loses its effectiveness by exceeding the collision force at more than a certain level.

4. EFFECT OF CONVECTION

4.1. *Experimental appratus and experimental method*

Two kinds of apparatus were set to investigate the effect of convection. One was to generate convection by rotating a solid in the test water, as shown in Fig. 8. Test water having a volume of about 3 ml was placed in a test tube and sealed with oil. A copper bar having a diameter of about 5 mm was inserted into the test water in the test tube vertically, and the test tube was set in a glass cup containing ethylene glycol solution. The copper bar was fixed to a stainless steel pipe to prevent it from absorbing heat from the outside. Temperature measurement was carried out by soldering a thermocouple onto the copper surface just above the water–oil interface. By adding liquid nitrogen to the cup, temperature of the cooling medium was controlled and the cooling rate was fixed at 0.3 K min^{-1}. At each degree of supercooling, the bar was rotated at 10–350 rpm and then stopped and

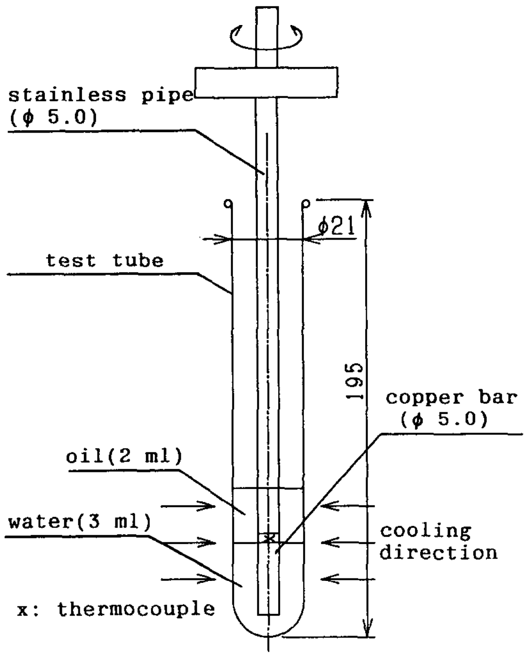


FIG. 8. Experimental apparatus for the rotating bar.

rotated again inversely several times. This rotational speed is equivalent to a surface speed of about 2.6–90 mm s^{-1}.

The other type of apparatus was used to generate convection by applying a jet stream in the test water, as shown in Fig. 9. Test water having a volume of about 6 ml was placed in a test tube and sealed with oil. Two glass tubes each having an outer diameter of about 3 mm were inserted. One of them was to measure the water temperature, closed at the tip and fitted with a thermocouple inside. The ability of glass surface to freeze water is so low that there is almost no effect by dipping the glass bar in test water, but the temperature of the oil near the water–oil interface was measured. The other glass tube had a nozzle at the tip having a diameter of about 0.1–0.3 mm, and the other end was connected to a piston and filled with pure water. By applying the same cooling method as before, the test water was cooled at a constant cooling rate of 0.18 K min^{-1}. The volume of the test water had to be large enough for this kind of experiment, and so the cooling rate had to be low enough to maintain a uniform temperature distribution. The accuracy was within 0.02 K min^{-1}. At each degree of supercooling, a small quantity of test water in the test tube was transferred into the glass tube by pulling the piston slightly, and various levels of jet stream were applied from the tip of the glass tube by pushing the piston at various degrees of force or giving some shock to the connecting hose by hitting it. The experiment was carried out until freezing took place and was counted as one experiment. Furthermore, there were two types of tip shapes, one was straight and the other was J-shaped. Hence, two kinds of streams, namely, upward stream and downward stream, were investigated.

4.2. *Experimental results*

The experimental results of rotating a copper bar in supercooled water are shown in Fig. 10(a) in the form of the number of runs of the experiment against

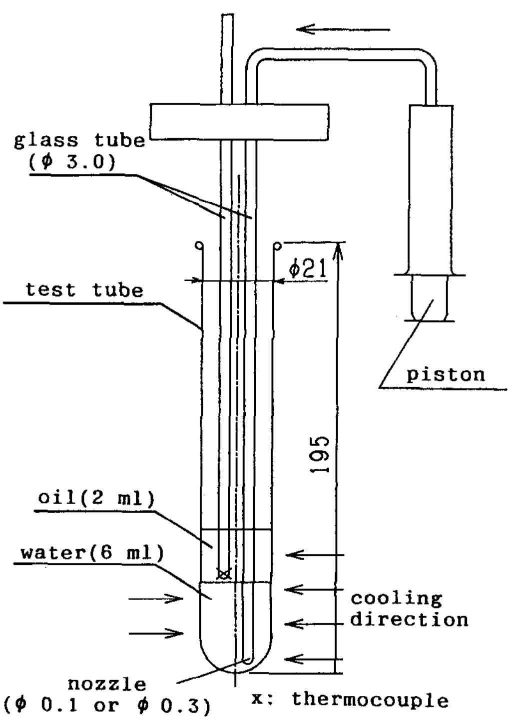
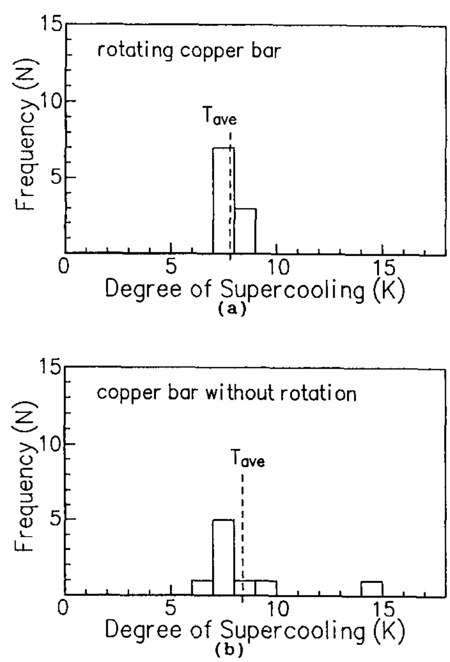


FIG. 9. Experimental apparatus for the jet stream.



FIGS. 10(a) and (b). Frequency distributions.

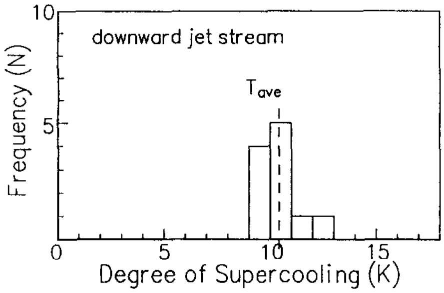


FIG. 11. Frequency distribution.

the degree of supercooling at the instant of freezing. Experimental results without rotating the copper bar are shown in Fig. 10(b). No significant difference can be observed. Although the copper surface is considered to have an effect on the initiation of freezing, and so the degree of supercooling at freezing was less than that of a glass bar, the instant of freezing could not be observed during rotation nor within 1 or 2 min after the rotation. Therefore, it can be concluded that forced convection in the range performed in this report has no significant effect on the ability of supercooled water to freeze.

The experimental results of applying a downward stream to supercooled water periodically are shown in Fig. 11. The initial ice for many of the experiments was observed at the tip, but the instant of freezing could not be observed while applying the flow nor within 3 min after the flow. This behavior was the same as for the upward stream. Therefore, it shows that there is no relationship between such a stream and the freezing of supercooled water.

5. EFFECT OF VIBRATION

5.1. *Experimental apparatus and experimental method*

The effect of pressure fluctuation on supercooled water was investigated by applying some horizontal vibrations to the cylindrical enclosure containing the supercooled water. The reason for adopting such an enclosure was to separate the effect of pressure fluctuation from the effect of the water interface. The apparatus for this experiment is similar to the one used to investigate the effect of cooling rate on the degree of supercooling at freezing in another report [4], as shown in Fig. 12(a). The center of gravity was lowered by reducing the size of the coolant container, fixing a two rail bearing at the bottom, and setting the connecting bar with a vibrator at a level 7 mm below the heat transfer surface which is the center of gravity. Measurement of vibration was carried out using a gap sensor. The frequency, the amplitude and the cooling rate were varied from 0 to 500 Hz, from 0 to 810 μm and from 0.6 to 18 K min^{-1}, respectively. Each experiment was carried out under constant frequency, amplitude and cooling rate. The effect of the horizontal vibration was studied by comparing the results

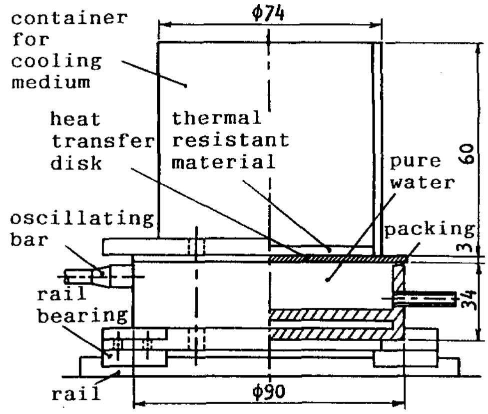


FIG. 12(a). Experimental apparatus for the oscillating enclosure.

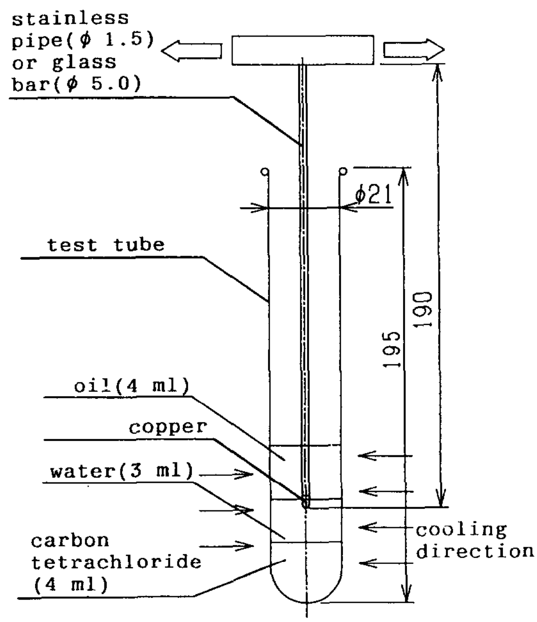


FIG. 12(b). Experimental apparatus for the oscillating bar.

with those under no vibration. Liquid nitrogen was used as the cooling medium, and the cooling rate was fixed by selecting the type of thermal resistant material and its thickness. The accuracy of the cooling rate was within 10%.

The effect of vibrating a bar inserted in the test water on the degree of supercooling at freezing was also investigated. The experimental apparatus is shown in Fig. 12(b). A glass bar, 5 mm in diameter, and a copper bar, 1.5 mm in diameter, were selected as two oscillating bars. The majority of the copper bar, except the tip, was made of stainless steel to prevent heat from flowing in. The fixed end of the bar was connected to the oscillator, and the tip of the bar was dipped in the test water. Various kinds of horizontal vibrations were applied varying the frequency and the amplitude. The temperature of ethylene glycol as a cooling medium was controlled in a cold bath by adding liquid nitrogen, and the coolant was transferred and circulated to the test section. The test water was cooled at a constant cooling rate of 0.3 K min^{-1}. During the experiment, a constant vibration was provided all the way through until freezing took place. The effect of such vibration was investigated by comparing the results with the results under no vibration.

5.2. *Experimental results*

Table 1 shows the average degree of supercooling at freezing obtained by performing experiments of cooling the enclosure containing the test water, during which a horizontal vibration of a certain frequency and a certain amplitude was given. Five to 50 runs of experiments were conducted in each experimental condition. The cooling rates for all the experiments were fixed at 18 K min^{-1}. All the values of the table, including the one with no vibration, fitted within a 1 K range. Therefore, it was found that the external factor of vibrating an enclosure containing test water had no significant effect on the freezing of supercooled water. One hundred and twenty days were spent completing all the experiments, and 20 experiments were carried out without vibration both at the beginning and at the end of the period. It was found that the average degree of supercooling at freezing increased by about 2.6 K. It seemed to be caused by transition of the characteristics of the copper surface due to oxidization [4]. Hence, all the values in the table represent results taken after the modification on the sixtieth day.

Under a low cooling rate, the volume of water having a higher degree of supercooling is larger than the one under a higher cooling rate when the heat transfer surface approaches the same temperature. Hence, the effect of vibration may appear more sensitive under a low cooling rate. For this reason, experiments were carried out under three kinds of fixed cooling rates. Conditions on vibration were fixed to a frequency of 50 Hz and an amplitude of 90 μm. The results are shown in Table 2 as the average degree of supercooling at freezing, and compared with the results under no vibration. It shows that there is no effect of vibration even under a low cooling condition. It also indicates that the average degree of supercooling at freezing decreases as the cooling rate decreases, which has already been clarified in our previous report [4].

Table 1. Average degree of supercooling at freezing (oscillating an enclosure)

Amplitude (μm)	Frequency (Hz) 0	5	50	100	300	500
0	10.8					
1.2			10.4	11.1	10.1	10.4
2					10.5	
6			9.9			
18				10.8		
30			10.4			
90			10.0			
810		10.8				

Table 2. Average degree of supercooling at freezing (oscillating an enclosure)

	Cooling rate ($K\ min^{-1}$) 18	1.8	0.6
Still (K)	10.8	8.3	6.9
Oscillating (K) (50 Hz, 90 μm)	10.0	7.2	7.1

Table 3 shows the average degree of supercooling at freezing obtained by inserting a glass bar or a copper bar as an oscillating bar into the test water and applying various levels of vibrations during cooling. In the case of the glass bar, the average degree of supercooling at freezing fitted within a 0.5 K range under any condition. A similar tendency was also obtained for the copper bar. Therefore, it was found that there is no effect of vibration using oscillating bars. It was not possible, however, to increase the vibrational power to the level at which Nagashima *et al.* [2] had reported that there was an effect. The test water had mixed with the oil forming many water droplets in oil under such a condition.

There is the possibility of suppressing the effect by applying the vibration continuously, since such vibration may separate the ice embryo from the oscillating surface. Hence, experiments to apply intermittent vibration for a few seconds at each 0.5 K under a constant cooling rate were attempted. However, no effect on the freezing of supercooled water was found for such an external factor.

6. EFFECT OF SHOCK

6.1. *Experimental appratus and experimental method*

The enclosure containing the test water shown in Fig. 12(a) was set stationary and cooled at a constant cooling rate of 0.6 K min^{-1}. At each degree of supercooling, shock was applied to the test water by dropping a steel ball from a fixed height onto the thermal resistant material placed on top of the heat transfer disk. The effect of such shock to supercooled water

Table 3. Average degree of supercooling at freezing (oscillating an inserted bar)

Glass (K)	Copper (K)	Frequency (Hz)	Amplitude (μm)
12.8	11.7	0	0
12.5	12.1	5	1500
—	11.5	20	800
13.0	10.5	50	450
12.8	10.8	200	50

was investigated. This apparatus was not perfectly enclosed, since there was a small sized tube connected near the bottom to absorb volumetric expansion due to temperature change and phase change. Fluctuation of the heat transfer surface could not be measured directly, since it was covered with the thermal resistant material. Hence, the behavior of the surface was measured at ambient temperature using another apparatus, whose thermal resistant material had a small hole so that there was an exposed part on the top surface of the disk to measure the vertical displacement.

A similar kind of experiment was performed. The test water was poured into a test tube and sealed with oil. While the water was cooled at a cooling rate of 0.25 K min^{-1}, shock was applied to the water at each degree of supercooling by hitting the outer surface of the test tube at various levels using a stick. The cooling method was the same as the one used in Section 2. The accuracy was within 0.02 K min^{-1}. Using such apparatus, the effect of shock on supercooled water was investigated by indirect hitting.

Furthermore, a glass bar or a copper bar was inserted in the test water in a test tube, as it was in Section 5, and instead of applying a horizontal vibration, a horizontal shock was applied to the bar, by hitting near the fixed end horizontally at each degree of supercooling.

Experiments on applying a vertical shock were also carried out by stopping the falling bar forcibly at each degree of supercooling.

6.2. *Experimental results*

Experiments of dropping a steel ball on top of the enclosure from 50, 150 and 250 mm heights were carried out. Figure 13 shows the behavior of the heat transfer surface due to falling impact measured at the center of the surface using a gap sensor. The behavior of the surface caused by such an impact is dumping motion, and hence the maximum displacement was taken as a parameter. Approximately 10 experiments were carried out for each falling height condition, but there was no sign of any relationship between the shock and the degree of supercooling at freezing nor the instant of freezing. This enclosure was tightened with packing material placed between the heat transfer disk and the water container, and there was an effect when the tightening was loosened slightly. Ice appeared from the edge at the instant of applying the shock.

At each degree of supercooling, several levels of shock were applied by hitting the outer surface of the test tube. However, there was no effect on the freezing of supercooled water.

The experimental results obtained by applying horizontal shock on the glass bar whose tip was dipped in test water are shown in Fig. 14, together with the results obtained without inserting a glass bar and the results with a glass bar inserted without applying shock. This figure shows that there is no difference

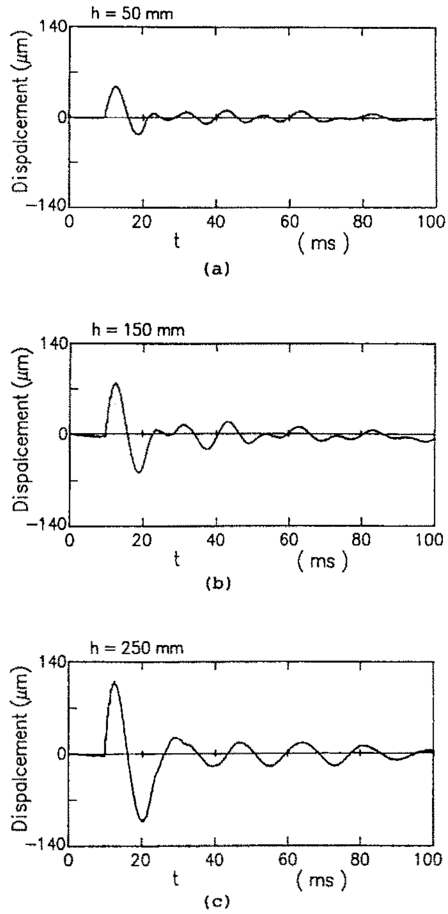


FIG. 13. Behavior of the heat transfer surface due to a falling impact (impact on an enclosure).

when just dipping the glass bar in the test water but that there is a significant change when applying shock to the inserted bar. The average degree of supercooling was lowered by about 4 K. The moment and the position of ice appearance were at the instant of applying shock at the point of contact of the glass bar and the water–oil interface. Hence, some dynamical relationship between the interface and the glass bar may have some effect on the freezing phenomenon.

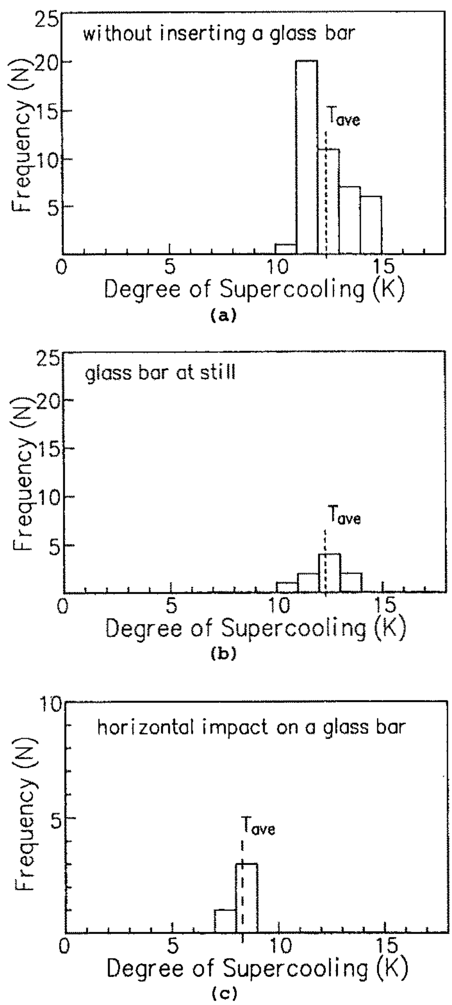
Concerning the shock transferred by the falling glass bar and the forcible stop, no effect was obtained due to such shock.

7. OVERALL DISCUSSION OF THE EXTERNAL FACTORS

Based on the experimental results presented in this report, the effects of various kinds of external factors are considered below.

The external factors which have the effect of freezing supercooled water are:

(i) rubbing glass against glass in the test water;



FIGS. 14 (a)–(c). Frequency distributions.

(ii) collision of glass against glass in the test water;

(iii) shock on the edge of the heat transfer disk when the apparatus is loosely tightened; and

(iv) horizontal shock on the water–oil interface by a glass bar.

The external factors which do not cause supercooled water to freeze are:

(v) forced convection by rotating an object in the test water;

(vi) forced convection by applying a jet stream in the test water;

(vii) horizontal vibration to an enclosure containing the test water;

(viii) horizontal vibration to a glass bar whose tip is dipped in the test water;

(ix) shock by a falling object on top of an enclosure containing the test water;

(x) shock by hitting the outer surface of a test tube containing the test water; and

(xi) shock by the forcible stopping of a falling object in the test water.

In all the items (i)–(iv), forced convection and pressure fluctuation due to vibration or shock exist. However, from items (v) to (xi) we know that such external factors have no effect on the freezing of supercooled water. Factors such as convection, vibration or shock add some positive energy to the water molecules, not helping the water to freeze. The evidence can be found in item (ii). The effectiveness of freezing supercooled water decreased when the collision force exceeded more than a certain level.

The reasons for the effectiveness in items (i)–(iv) are considered below

Case (iii) can be taken as being similar to case (ii), since the packing material collides with the water container holding a small quantity of water between them. In both cases, the solid surface restricts the motion of the water molecules adjacent to the surface. Hence, by colliding solids in supercooled water, the water molecules get closer to each other whose motions are restricted by a solid surface, and it causes induction of the growth of an ice embryo (cases (ii) and (iii)). Although water is an incompressible material macroscopically, a group of water molecules, small enough to form an embryo, are easily brought closer by a weak external force.

The same explanation can be applied for collision between the liquid interface and a glass surface (case (iv)).

The same explanation can also be applied for the rubbing of a solid against a solid in the test water, since a small quantity of water also exists between the solids (case (i)).

8. CONCLUSION

In relation to the problem of controlling the freezing phenomenon of supercooled water, investigations were carried out to observe the effect of various kinds of external factors on supercooled water experimentally, and the following conclusions were obtained.

(i) Various levels of rubbing and collision were applied in the supercooled water, and the effect was investigated. It was found that there is a tendency to decrease the average degree of supercooling at freezing when glass is rubbed reciprocally against glass in the test water with a higher frequency or higher amplitude. It was also found that the average degree of supercooling at freezing decreases down to 5 K by increasing the collision force of solid in the test water. No effect, or rather inverse effect, was found by increasing the collision force by more than a certain level.

(ii) Various levels of convection, vibration and shock were applied to supercooled water, and the effect was investigated. However, it was clarified that such external factors do not help the supercooled water to freeze.

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REFERENCES

1. T. Kashiwagi, S. Hirose, S. Itoh and Y. Kurasaki, Effects of natural convection in a partially supercooled water cell on the release of supercooling, *Trans. JSME* **53,** 490, 1822 (1987).
2. A. Nagashima and T. Nakamura, *Jap. Heat Transfer Symp.* **14,** a301, 88 (1977) (in Japanese).
3. R. S. Johannsen, Some experiments in the freezing of water, *Science* **108,** 652 (1948).
4. A. Saito, S. Okawa and A. Tamaki, Fundamental research on supercooling phenomenon on heat transfer surface, *Proc. 2nd Int. Symp. on Cold Regions Heat Transfer*, Hokkaido Univ., p. 79 (1989).

RECHERCHE FONDAMENTALE SUR LES FACTEURS EXTERNES AFFECTANT LE GEL D'EAU SURREFROIDI

Résumé—En relation avec le problème du surrefroidissement pour les systèmes de stockage de la glace, différentes expériences sont conduites pour trouver quelques facteurs qui contrôlent le phénomène de surgel. On a considéré les facteurs externes suivants : présence de verre dans l'eau, collision d'un solide dans l'eau, convection générée par la rotation d'un solide dans l'eau, écoulement en jet, vibration et choc. On trouve que des facteurs comme la convection, la vibration et le choc n'ont pas d'effet sur le gel. Ils semblent ajouter une énergie positive à l'eau. D'un autre côté, la collision ou le frottement entre solide et liquide aide le gel de l'eau. On pense que la croissance du germe de glace est induite par le rapprochement des molécules d'eau dont le mouvement est limité par un solide ou la surface liquide.

GRUNDLEGENDE UNTERSUCHUNG ÜBER DAS GEFRIEREN VON UNTERKÜHLTEM WASSER UNTER DEM EINFLUSS ÄUSSERER FAKTOREN

Zusammenfassung—Im Zusammenhang mit dem Problem der Unterkühlung von Eisspeichern werden verschiedene Arten von Experimenten durchgeführt. Ziel ist es, einige Größen zu finden, die das Unterkühlungsphänomen maßgeblich beeinflussen. Äußere Faktoren sind dabei : Reibung von Glas auf Glas in Wasser, Feststoff-Kollisionen in Wasser, durch einen rotierenden Festkörper verursachte Konvektion in Wasser, Strahlströmung, Vibration sowie Erschütterung. Es hat sich gezeigt, daß Konvektion, Vibration und Erschütterung keinen Einfluß auf das Gefrieren von unterkühltem Wasser haben. Sie scheinen dem Wasser nur einige positive Energie zuzuführen. Im Gegensatz dazu unterstützen Zusammenstöße und Reibung zwischen Festkörpern sowie zwischen einem Festkörper und einer Flüssigkeitsfläche in unterkühltem Wasser das Gefrieren. Die Autoren nehmen an, daß das Wachstum eines Eiskeims durch einen engeren Zusammenschluß von Wassermolekülen hervorgerufen wird, deren Bewegungen durch den Festkörper bzw. die Flüssigkeitsfläche eingeschränkt waren.

ИССЛЕДОВАНИЕ ВЛИЯНИЯ ВНЕШНИХ ФАКТОРОВ НА ЗАМЕРЗАНИЕ ПЕРЕОХЛАЖДЕННОЙ ВОДЫ

Аннотация—В связи с решением задачи переохлаждения в накопителях льда проводились различные эксперименты, целью которых являлось установление факторов, определяющих явление переохлаждения. Были выявлены следующие внешние факторы: трение стекла о стекло в воде, столкновение твердых тел в воде, конвекция за счет вращения твердого тела в воде, струйное течение, вибрация и удар. Найдено, что такие факторы, как конвекция, вибрация и бесконтактный удар не оказывают влияния на замерзание переохлажденной воды, а лишь сообщают ей некоторую положительную энергию. С другой стороны, столкновение или трение между твердыми телами или твердым телом и поверхностью жидкости в переохлажденной воде способствуют ее замерзанию. Предполагается, что рост зародыша льда вызван сближением молекул, движение которых ограничивалось поверхностью твердого тела или жидкости.