Int. J. Heat Mass Transfer. Vol. 20, pp. 693–699. Pergamon Press 1977. Printed in Great Britain

THE EFFECTS OF DENDRITIC ICE FORMATION IN WATER PIPES

R. R. GILPIN
Department of Mechanical Engineering, University of Alberta, Edmonton, Alberta, Canada T6G 2G8

(*Received* 16 *July* 1976 *and in revised form* 24 *September* 1976)

Abstract—When quiescent water in a pipe is cooled ice growth normally does not nucleate until the water temperature near the pipe wall has been supercooled 4–6°C below freezing. The growth of ice into this supercooled water results in the formation of dendritic ice. Studies were made of the effect of this ice form on the pressure gradient required to start flow in a partially frozen pipe. It was found that under some conditions the growth of dendritic ice in a pipe can result in a flow blockage when only a small fraction of the water in the pipe is frozen.

NOMENCLATURE

A,	cross-sectional area of pipe (internal);
C,	specific heat of water;
L,	latent heat of fusion of ice;
P,	perimeter of pipe;
t,	time;
$\dot{q}$,	heat flux through pipe perimeter, P;
w_d,	volume fraction of dendritic ice;
w_s,	volume fraction of solid ice;
ΔT_s,	amount of supercooling in water;
ρ_i,	density of ice;
ρ_w,	density of water.

INTRODUCTION

WHEN water is cooling it must always cool below 0°C, that is supercool, to some extent before ice nucleation will occur. The concept of a nucleation temperature which is different from the phase equilibrium temperature is common to other phase change phenomena such as boiling. For normal tap water the nucleation temperature is usually 4–6°C below freezing [1]. The phenomenon of supercooling is important because the ice growing into supercooled water does not form as a solid layer of ice which is the form of ice normally observed. Instead it grows as dendritic ice which consists of thin plate-like crystals of ice interspersed in the water [2]. If the water is in a large container that is cooled rapidly the supercooling may be confined to a thin boundary layer adjacent to the cold walls, in which case only a small amount of dendritic growth would occur at the walls. This dendritic ice would soon be engulfed by the growth of a solid layer of ice forming on the container walls. Alternatively, if the container cools slowly the bulk of the water may be supercooled when nucleation occurs. In this situation the dendritic ice growth would occur throughout the entire volume of the container. This could, for example, occur in a well insulated water pipe or one that was exposed to an environment only slightly below freezing.

The existence of dendritic ice growth in water utility pipes has been documented for some time [3]. It is occasionally reported that "slush" ice, that is a mixture of ice crystals and water, is observed when flow is started in a pipe that has been exposed to a subfreezing environment. This is presumably the result of dendritic ice that has been broken loose by the water pressure and would only be observed if the pressure was sufficient to break through the dendritic structure. The question then arises as to whether the dendritic ice in some other situations might be strong enough to cause a pipe blockage. If this is the case the usual calculations of the time required for a pipe to become blocked by ice would be greatly in error. These calculations, for example those in the *ASHRAE Handbook* [4], are commonly based on the assumption that the ice would grow in from the pipe walls as a solid annulus. This reference is, however, negligent in not mentioning the possibility that dendritic ice could form in the pipe.

Brown [5] and later Dorsey [1] have in fact suggested that dendritic ice growth may be responsible for the commonly observed phenomena that a hot water pipe is more likely to burst when frozen than a cold water pipe is. The argument depends on the fact that heating water destroys the ice nuclei in it thus lowering its nucleation temperature. As a result more dendritic ice would form in the hot water pipe preventing water from escaping from it as it froze. There has, however, been very little systematic research into the effects that dendritic ice would have in a pipe. Most of the engineering research on pipe freezing has been concerned with the growth of a solid annulus of ice in a pipe [6, 7], although the occurrence of supercooling has occasionally been noted [7]. On the other hand the research on dendritic ice has primarily been concerned with the physics of the phenomenon particularly as it relates to the freezing of supercooled water droplets in the atmosphere [2, 8, 9]. In these latter studies growth rates, crystal morphologies, and nucleation temperatures have been measured.

A number of the factors that could be important in determining the extent of dendritic ice growth in a pipe can be anticipated. These factors are the ice

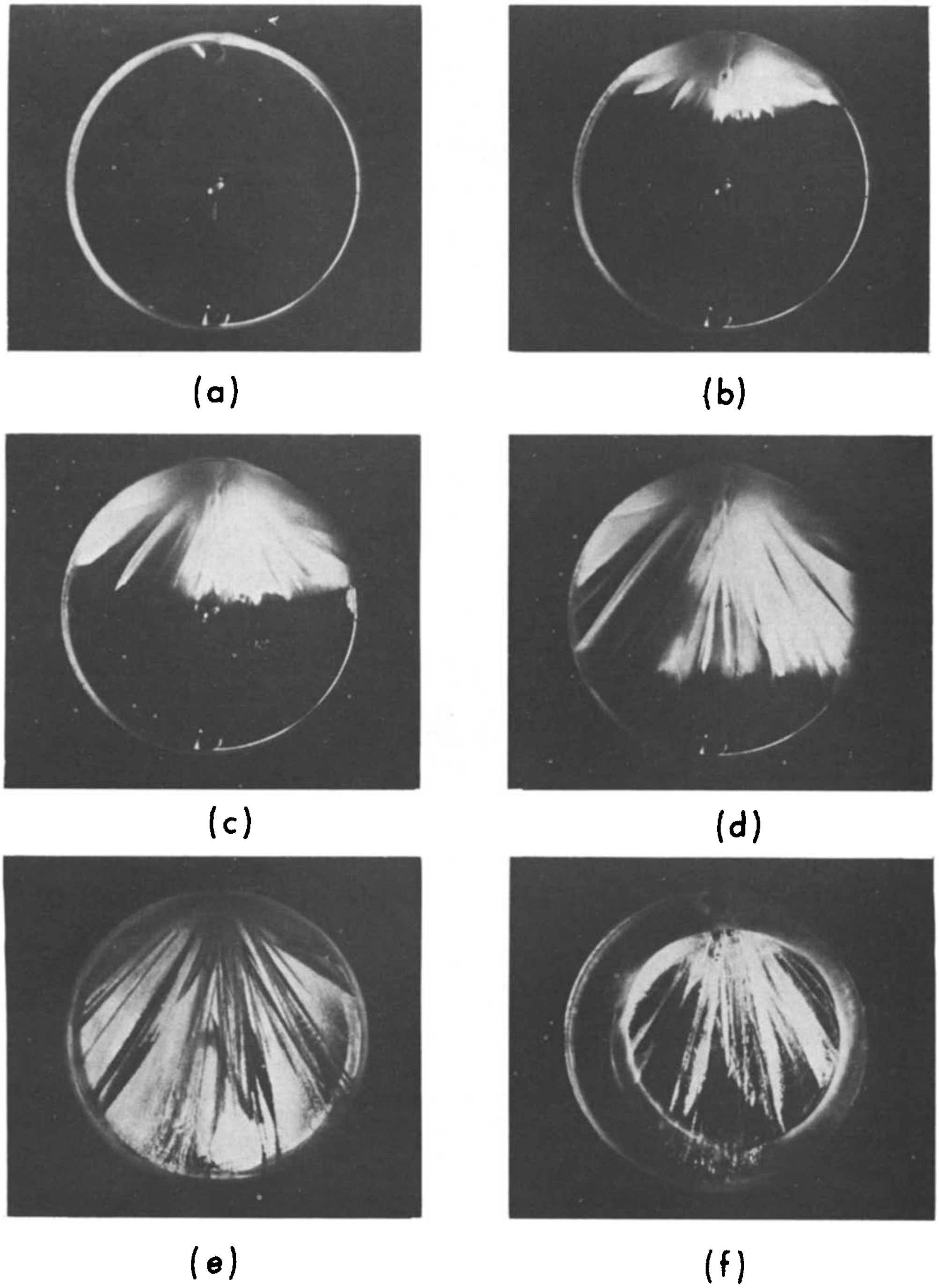

FIG. 1. The growth of ice in a pipe (a) before nucleation, (b), (c) and (d) during dendritic ice growth, (e) and (f) during annular ice growth.

nucleation temperature, the cooling rate of the pipe, the pipe diameter and the velocity, if any, of the water in the pipe. Some studies have been made on the effects of velocity on the amount of supercooling in a pipe [10]. Also information exists from which the effects of cooling rate can be assessed [11, 12]. In this study the effects of ice nucleation temperature and pipe diameter were studied for a pipe with no flow and a very slow cooling rate. The primary objective being to determine whether dendritic ice growth could be responsible for the blockage of a water pipe.

THE PIPE FREEZING PROCESS

To qualitatively observe the freezing process in a horizontal cylinder a number of tests were done with a short length of large diameter (150 mm) pipe. The ends of this pipe were blanked off with plexiglass windows so that photographs could be taken of the ice growth across the cross-section of the pipe. The pipe was placed in a cold chamber and allowed to come to equilibrium with its surroundings. Figure 1(a) shows the cross-section of the pipe containing water supercooled to −3°C just before ice growth was

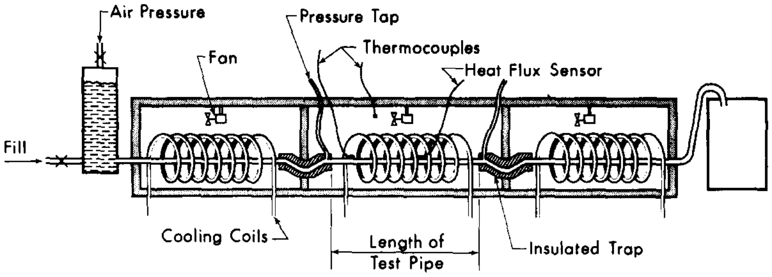

FIG. 2. Experimental apparatus used to measure "start-up" pressure in a partially frozen pipe.

nucleated. Figures 1(b–d) show the growth of ice dendrites from the nucleation center near the top of the cylinder until the cross-section has been blocked by the dendritics. The total time required for this dendritic ice growth phase to be completed is about 30 s. At the end of this phase the temperature of the remaining water in the pipe has returned to 0°C. The fraction of the pipe volume occupied by dendritic ice, w_d, is directly proportional to the amount of supercooling, ΔT_s, existing when ice nucleated. That is

$$w_d = \frac{\rho_w C(\Delta T_s)}{\rho_i L} \qquad (1)$$

where $\rho_w C(\Delta T_s)$ is the heat taken up in returning the water temperature to 0°C, and $\rho_i L$ is the heat released during the dendrite growth. The inclusion of the density ratio, ρ_w/ρ_i, assumes that the excess volume of water that results from the expansion that occurs in the freezing process can flow out of the pipe.

After the water temperature has returned to 0°C no more dendritic ice growth occurs. An annulus of solid ice then begins to grow slowly in from the inside wall of the pipe. The photographs in Figs. 1(e) and (f) were taken 3 and 18 h respectively after the dendritic ice growth had occurred. The volume fraction of solid ice, w_s, formed at some time during the annular ice growth phase is approximately equal to the ratio of the total heat lost from the pipe, after the dendritic ice growth has occurred, to the total heat loss required to freeze the pipe solid. This approximation is valid since the changes in internal energy that occur in the pipe material and ice after it is frozen are very much smaller than the heat release caused by the latent heat of fusion of the ice. The integrated heat flux through the pipe wall can therefore be used to calculate the volume fraction of solid ice in the pipe.

$$w_s = \frac{P}{\rho_i A L}\int_t \dot{q}\,\mathrm{d}t \qquad (2)$$

where P is the perimeter of the pipe where the heat flux, $\dot{q}$, is measured and A is the cross-sectional area of the water in the pipe.

As mentioned previously one anticipated consequence of dendritic ice growth is that a pipe may be blocked sooner if dendritic ice growth occurs than if it does not. To determine whether blockage could be caused by dendritic ice the pressure gradient required to start flow through a partially frozen pipe, as in Figs. 1(e) and (f), was measured. The next sections will describe the experimental apparatus used for these measurements and the results obtained.

EXPERIMENTAL APPARATUS

Figure 2 shows the experimental apparatus used for the main part of the tests. The apparatus basically consists of a cold chamber 0.3 × 0.3 × 2.4 m(1 × 1 × 8) that was divided into three compartments. The air temperature in each compartment could be maintained at the desired level by circulating a coolant fluid, methal hydrate, from a controlled temperature bath through a helical coil in the chamber. Fans maintained a vigorous air circulation in each compartment to produce a uniform temperature distribution. The test pipe was normally located in the center compartment which was maintained at the desired temperature below freezing. The two compartments on either side of the test section were used to decrease end effects. Their temperatures were held at 0°C. Traps consisting of insulated U-shaped sections of pipe at each end of the test section were found to be useful in eliminating convection into and out of the test pipe.

To avoid disturbing the ice growth in the pipe thermocouples were not inserted directly into the pipe. Instead thermocouples used to measure the temperature of the water in the pipe were taped to the outside of the pipe. A small amount of insulation directly over the thermocouples insulated them from the air temperature. In some preliminary tests a thermocouple was inserted inside the pipe so that the temperatures of the water in the pipe, the pipe wall, and the air temperature could be compared. It was found that if the air and pipe wall temperatures were approximately in equilibrium, that is within 1°C of each other, then the temperature of the pipe wall and the water temperature in the pipe were essentially the same, within 0.1°C of each other. All the thermocouples used were copper–constantan and were calibrated against an NBS tracable platinum resistance standard. In addition to the thermocouples a heat flux sensor was attached to the outside of the test pipe. The output from this sensor was used to calculate the amount of ice growth in the pipe.

The pressure drop across a section of test pipe was measured by a differential pressure transducer connected between two pressure taps in the pipe. The lines to the pressure taps were heated with electrical resistance tape to prevent ice formation in these lines.

In a typical experiment the air temperature in the test chamber would be set at the desired value and the pipe, filled with water, would be allowed to come to equilibrium at this temperature. It was found that the lowest nucleation temperature was obtained if the test pipe was filled from the hot water tap before each test. Using this procedure ice nucleation occurred naturally in the pipe at a supercooling of −5 to −6°C. To produce ice growth in the pipe at a supercooling less than this value and thus simulate the effects of a lower nucleation temperature ice growth was initiated artificially. This was done by one of two methods. In the first method used, a tee joint was added to the pipe outside the section where the pressure measurement was made. The one end of the tee was blanked off and a cooling coil soldered to it. To initiate ice growth with this device, the cooling fluid at −10°C or colder was passed through the cooling coil when the supercooling in the test pipe had stabilized at the desired level. It was later discovered that ice growth in the pipe could also be initiated at any desired supercooling by striking the end of the pipe with a sharp blow. Since the results appeared to depend only on the supercooling at which ice growth was initiated and not on the method of initiation, the later and more simple method of initiation was used in most tests. Ice growth in the pipe could be detected by a rapid rise in the temperature of the pipe wall back to 0°C. Once initiated the ice growth spread from the nucleation point throughout the pipe in a few minutes.

At some time after the dendritic ice growth had been completed the pressure gradient required to start flow in the pipe was measured. This was done by applying air pressure to the top of a water reservoir connected to one end of the pipe and recording the time history of the pressure drop across the test section of the pipe. The result was an initial rising pressure during which little or no flow could be observed coming out of the pipe. When the ice in the pipe broke loose the pressure dropped suddenly and a rapid flow of water mixed with ice crystals, a "slush" ice, came out of the pipe. The maximum pressure reached during each test was recorded as the "start-up" pressure; that is, the pressure required to start the flow. Dividing by the length of the test pipe gave the required pressure gradient.

Before the ice broke loose a small amount of water would flow through the dendritic matrix particularly for ice grown at supercoolings less than 4°C. If this water flowing through the dendrites was above freezing this could cause melting of the ice before the pressure reached a value where it broke through the ice. This problem was alleviated by having an upstream section on the pipe where the water was precooled to 0°C. Provided that water above 0°C did not reach the test pipe, the rate of pressure rise applied to the pipe appeared not to have a major effect on the "start-up" pressure. The time required to reach "start-up" pressure was varied from about 0.1–5 s.

In the course of the experimentation it was found that the pressure required to start the flow in a given pipe depended quite critically on the length of time between the initiation of the ice growth and the application of the pressure. This parameter which is related to the total volume fraction of ice grown in the pipe was varied during the tests. Additional parameters that were varied were the supercooling at which the ice was grown, the pipe diameter (6.35–25.4 mm), length of the test pipe (0.3–1.8 m), pipe material (copper and plastic were tried) and type of water (tap and distilled).

MEASUREMENTS OF THE "START-UP" PRESSURE

The pressure gradients required to start flow in a partially frozen pipe under various conditions are shown in Figs. 3–5. The pressure gradient in each case is plotted against the total volume fraction, w, of ice formed in the pipe at the time that the pressure was applied to the pipe. The volume fraction, w, is equal to the sum of the volume fraction of dendritic ice, w_d, and the volume fraction of annular ice, w_s. The volume fraction of dendritic ice, w_d, was calculated from equation (1) using the measured supercooling temperature at the time of ice nucleation. The volume fraction of solid ice growth was calculated from equation (2) using the integrated output of the heat flux sensor between the time that the dendritic ice growth occurred and the time at which pressure was applied to the pipe.

Figure 3 shows the effect of the initial supercooling in the pipe at the time of ice nucleation. This data was obtained by artificially nucleating the ice growth in one of several temperature ranges indicated on the figure. The data is for total volume fractions of ice less than 0.2. For a given amount of ice in the pipe it can be seen that the pressure gradient required to start the flow is as much as an order of magnitude greater for a pipe that supercooled 4–5°C before ice nucleated as opposed to one where the supercooled was 2.5°C or less. In fact for supercoolings of 2.5°C or less no significant start-up pressure was measured under any circumstance.

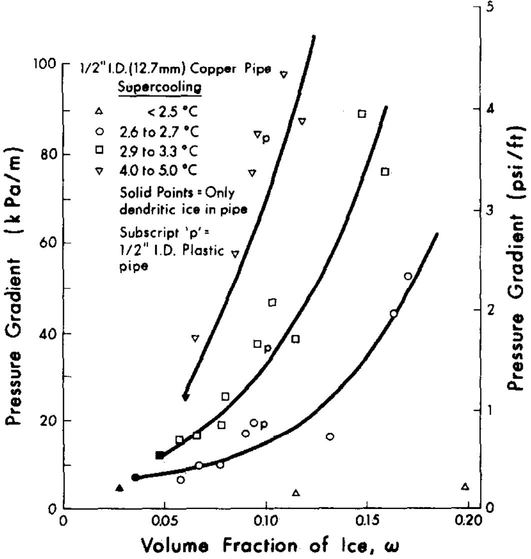

FIG. 3. The effect of nucleation temperature on the pressure gradient required to start flow during initial freezing period.

The solid data points in Fig. 3 are the measurements taken immediately after the dendritic ice growth was complete. The volume fractions of ice at these points are therefore the volume fractions of dendritic ice alone (approximately 5%). The pressure gradients required to start flow at this point are rather small, of the order of 20 kPa/m (1 psi/ft) and less. There is, however, a very rapid increase in the "start-up" pressure required during the first part of the annular ice growth phase, particularly for the higher amounts of supercooling.

Three data points are shown on Fig. 3 which were taken using a plastic pipe of the same internal diameter as the copper pipe. The results did not show any dependence on pipe material. This is perhaps not surprising in that an annulus of ice exists between the core region where the dendrites are and the actual pipe wall [see Fig. 1(f)].

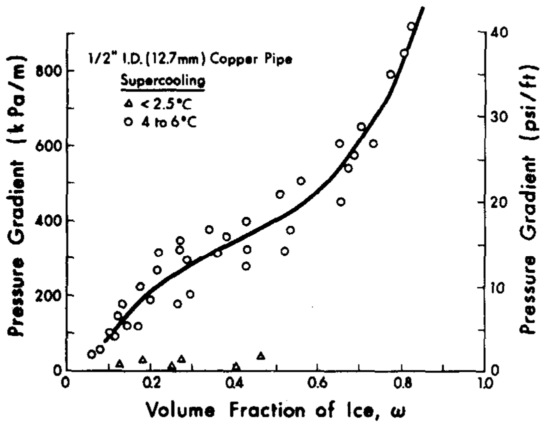

FIG. 4. Changes in the pressure gradient required to start flow throughout the freezing history of a pipe.

Figure 4 shows an extension of the data in Fig. 3 to large volume fractions of ice in the pipe. Most of the data in this figure is for ice that nucleated between −4 to −6°C. This is the range of temperatures in which spontaneous nucleation normally occurs in a water pipe. In this range of nucleation temperatures the scatter in the data obscured any systematic variation of "start-up" pressure with nucleation temperature. The scatter in the data of as much as ±30% could be due to the variation in the orientation of the dendritic ice crystals. In the clear plastic cylinder it was observed that the dendritic ice consisted of groups of more or less parallel crystal plates. The orientation of these plates relative to the pipe axis might be expected to have a significant effect on the pressure gradient required to start the flow.

The general behavior of the required gradient is a sharp increase for volume fractions of ice up to about 0.25, a region of relatively slowly increasing pressure gradient between 0.25 and 0.6, and finally a sharply increasing pressure gradient as the pipe approaches the fully frozen state. The initial sharp increase in pressure gradient could be due to a combination of factors. First the initial growth of an annulus of ice is occurring during this period. This annulus provides a bond between the dendritic matrix in the core of the pipe and the pipe wall. Second it was observed in the clear plastic cylinder that some changes in morphology of the dendritic ice continue to occur after its initial growth. Specifically, the dendritic crystals which originally grow with a highly branched "fern-like" structure change with time into thin but solid ice plates. The further rise in the required pressure gradient as the pipe approaches the fully frozen state is probably just due to the decrease in the diameter of the core region inside the solid ice annulus.

To assure that the "start-up" pressure measured was due to the dendritic ice growth and not just inertial effects in the water a number of runs were made where ice was nucleated artificially at a supercooling of 2.5°C or less. For the same total amount of ice growth the "start-up" pressure measured in these tests was insignificant in comparison to the pressure measured when the supercooling was in the range 4–6°C.

The data in Fig. 4 is an accumulation of data for various pipe lengths from 0.3 to 1.8 m. For the conditions of these tests it was found that the pressure required to start the flow increased linearly with the length of the test pipe. The implication of this observation is that the pressure applied to the inlet of the test pipe distributes itself as a linear pressure gradient along the length of the pipe. This provides the rationale for expressing the "start-up" pressure in terms of a pressure gradient.

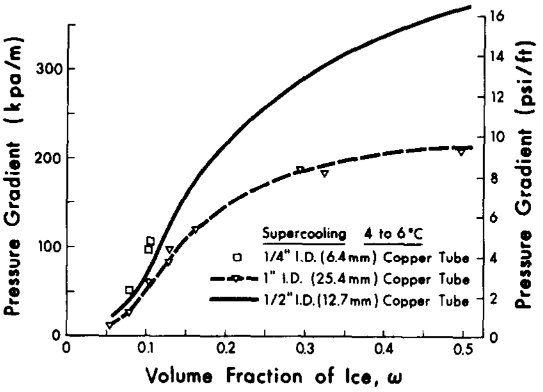

FIG. 5. The effect of pipe diameter on the pressure gradient required to start flow.

In Fig. 5 the effect of pipe diameter is shown. Data obtained for 1/4 in I.D. (6.4 mm) and 1 in I.D. (25.4 mm) pipes is compared to the curve fitted to the data from Figs. 3 and 4 for a 1/2 in I.D. (12.7 mm) pipe. The data show that the pressure gradient required to start flow in a large pipe is smaller than that required in a small pipe; however, the difference is not significant for volume fractions of ice less than about 0.2. At a volume fraction of 0.5 the 1 in I.D. pipe requires 50% less "start-up" pressure than the 1/2 in I.D. pipe. The pressure gradient required is, however, still quite large (about 200 kPa/m).

In these tests hot and cold tap water as well as distilled water were used. The only noticeable effect of the type of water was its effect on the temperature at which ice nucleated. As noted previously, the lowest nucleation temperatures of −5 to −6°C were obtained when the test pipe was filled directly from the hot water tap for each test. Water drawn in a similar way from the cold water tap normally nucleated in the range −4 to −5°C. If instead of filling the test pipe directly from the tap, it was filled from an open container the nucleation temperatures observed were as high as −3°C. These high nucleation temperatures existed even for distilled water. This behavior can be explained in terms of the heterogeneous theory of nucleation [1, 2]. That is, the water when it is exposed to the air picks up dust particles and other insoluble impurities which can act as ice nucleating centers. The effectivity of these ice nuclei is, however, destroyed by prolonged contact with water and particularly by contact with hot water.

Efforts were made in these tests to minimize the temperature differences that existed across and along the test pipe. This was done to ensure that natural convection currents would be small prior to the time of ice nucleation. The growth of ice dendrites into supercooled water does, however, generate its own temperature gradients. A study of this phenomenon has shown that these temperature gradients produce natural convection currents only when the supercooling of the water is less than about 2.5°C [13]. For greater amounts of supercooling the ice growth occurs too quickly for the currents to develop. It was also found that, because of the natural convection that occurs, a container that has supercooled less than about 2°C when ice nucleates, will not be entirely filled by the dendritic ice that forms. This observation is consistent with the measurements reported in this paper which showed that no "start-up" pressure existed when the ice formed at these small supercoolings.

Also of interest is the effect that a high rate of cooling at the time of ice nucleation would have on the subsequent dendritic ice growth. Investigations are continuing into this effect.

CONCLUSIONS

The main conclusion to be drawn from this study is that dendritic ice may be responsible for the blockage of a water pipe under certain conditions. The importance of this conclusion is that the dendritic ice could block a pipe much sooner than would be predicted on the basis of an assumed annular growth of ice. If the growth of an ice annulus was the only freezing mechanism one would expect that flow could be started in the pipe at any time up until the pipe was frozen solid. The only effect of the annulus of ice would be that it would increase the pressure drop in the pipe for a given flow rate. This would mean, for example, that if a water service line into a house was partially frozen with only an annulus of ice formed, the flow from the water main could be started and the ice melted out. On the other hand, if the pipe had supercooled significantly before ice nucleated, thus forming dendritic ice in the pipe, it may not have been possible to start the flow even for the same total amount of ice in the pipe. For example, a 0.5 in I.D. (12.7 mm) pipe which had supercooled 4–6°C before ice nucleated would require a pressure gradient of 200 kPa/m (10 psi/ft) to start the flow when only 20% ($w = 0.2$) of the water in the pipe was frozen. For a typical water main pressure of the order of 300 kPa (45 psi) this amount of ice would cause blockage of the flow in a pipe 1.5 m (4.5 ft) in length. The length of time required to freeze 20% of the water in the pipe would be, neglecting heat capacity, 20% of the time estimated for the pipe to be blocked by a solid annulus of ice. A finite pressure gradient is, in fact, required to start the flow at any time after dendritic ice growth has occurred. This means that for a long section of pipe that was exposed to freezing conditions a flow blockage could occur when as little as 5% of the water in the pipe is frozen. These results, therefore, have direct implications for heat-transfer calculations of the time required for a water pipe to become blocked by ice.

Acknowledgement—This work was supported by the National Research Council of Canada.

REFERENCES

1. N. E. Dorsey, The freezing of supercooled water, *Trans. Am. Phil. Soc.* **38**, 245 (1948).
2. C. A. Knight, *The Freezing of Supercooled Liquids.* D. Van Nostrand, Princeton, New Jersey (1967).
3. W. W. Brush, Freezing of water in subaqueous mains laid in salt water and in mains and services laid on land, *J. Am. Water Work Assoc.* **3**, 962 (1916).
4. ASHRAE, *Handbook of Fundamentals*, p. 305. Am. Soc. of Heating, Refrigeration, and Air Conditioning Engineers, New York (1974).
5. F. C. Brown, The frequent bursting of hot water pipes in household plumbing system, *Phys. Rev.* **8**(2), 500 (1916).
6. R. D. Zerkle and J. E. Sunderland, The effect of liquid solidification in a tube upon laminar-flow heat transfer and pressure drop, *J. Heat Transfer* **90**, 183 (1968).
7. J. C. Mulligan and D. D. Jones, Experiments on heat transfer and pressure drop in a horizontal tube with internal solidification, *Int. J. Heat Mass Transfer* **19**, 213 (1976).
8. H. R. Prappacher, Growth modes of ice crystals in supercooled water and aqueous solutions, *J. Glaciol.* **6**, 651 (1967).
9. R. B. Williamson and B. Chalmers, Morphology of ice solidified in undercooled water, in *Proc. Int. Conf. on Crystal Growth, Boston*, p. 739. Pergamon Press, Oxford (1966).
10. A. P. S. Arora and J. R. Howell, An investigation of the freezing of supercooled liquid in forced turbulent flow inside circular tubes, *Int. J. Heat Mass Transfer* **16**, 2077 (1973).
11. R. R. Gilpin, Cooling of a horizontal cylinder of water through its maximum density point at 4°C, *Int. J. Heat Mass Transfer* **18**, 1307 (1975).
12. R. R. Gilpin, A study of pipe freezing mechanisms, in *Proc. of the Symposium on Utilities Delivery in Arctic Regions.* Environmental Protection Service, Environment Canada (1976).
13. R. R. Gilpin, The influence of natural convection on dendritic ice growth, *J. Cryst. Growth* **36**, 101 (1976).

LES EFFETS DE LA FORMATION DENDRITIQUE DE LA GLACE DANS LES TUBES D'EAU

Résumé—Lorsque de l'eau au repos est refroidie dans un tube, la formation de la glace ne débute normalement que pour un sur-refroidissement de 4–6°C au dessous de la température de gel. La croissance de la glace dans cette eau sur-refroidie conduit à la formation de glace dendritique. Des études ont été faites sur l'effet de cette forme de glace sur le gradient de pression nécessaire pour réaliser l'écoulement dans un tube partiellement gelé. On a trouvé que dans ces conditions la croissance de glace dendritique dans un tube provoque un blocage de l'écoulement pour une petite fraction d'eau gelée dans le tube.

DIE AUSWIRKUNGEN DER BILDUNG DENDRITISCHER EISKRISTALLE IN ROHRLEITUNGEN

Zusammenfassung—Wird ruhendes Wasser in einem Rohr gekühlt, so bilden sich normalerweise erst dann Eiskristalle, wenn das Wasser in Rohrwandnähe um 4 bis 6 K unterkühlt ist. Dabei bilden sich dendritische Eiskristalle im unterkühlten Wasser. Es wurden Untersuchungen vorgenommen, um zu ermitteln, wie sich diese Eisart auf den Druckgradienten auswirkt, der zur Ingangsetzung einer Strömung in einem teilweise zugefrorenen Rohr erforderlich ist. Es zeigte sich, daß die Bildung dendritischer Eiskristalle in einem Rohr unter gewissen Bedingungen zu einer Blockierung des Strömungskanals führen kann, auch wenn nur ein kleiner Teil des Wassers ausgefroren ist.

ЭФФЕКТЫ ДЕНДРИТНОГО ОБРАЗОВАНИЯ ЛЬДА В ВОДОПРОВОДНЫХ ТРУБАХ

Аннотация — При охлаждении неподвижной воды в трубе образование в ней льда обычно не наступает до тех пор, пока температура воды у стенки трубы не понизится на 4–6°C ниже точки замерзания. Промерзание переохлажденной жидкости вызывает образование дентритного льда. Исследовалось влияние этой формы льда на градиент давления, необходимый для возникновения течения в частично замерзшей трубе. Найдено, что при определенных условиях рост дендритного льда в трубе может вызвать уменьшение расхода потока, когда в трубе заморожена только небольшая часть воды.