THEORY OF FORMATION AND DEPOSIT OF FRAZIL ICE

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ABSTRACT

This paper gives the results of experimentation carried on during two winters in a frazil ice flume set outside on the Campus of Laval University, to clarify our somewhat nebulous knowledge of frazil ice.

Many interesting results were obtained. It was first possible to arrive at a precise definition of this type of ice and state the necessary and sufficient conditions for its formation. Quantitative results were obtained which showed a good correlation between quantity of frazil ice produced and rate of water cooling at $0^{\circ}C$.

The fundamental property of frazil ice to adhere to certain objects in water was also closely scrutinized. Our tests always show that frazil ice is active as a clogging agent only during the very short period of its formation. They also indicate that it will never stick on certain types of material, some of which we have determined. These last results have, of course, wide practical significance.

Introduction

This article deals with the results of tests that were made during two winters in an ice flume set outside on the Campus of Laval University. These tests were conducted to clarify our present knowledge of frazil ice and establish the basic laws that govern the formation and deposit of this particular type of ice.

It is a well known fact that, in northern countries, water works in rivers and lakes must be designed with ice problems in mind. Some of these problems pertain to floating ice, anchor ice and ice jams in rivers; others to frazil ice. Much has been done recently on the mechanics of formation of ice covers and jams in rivers but no systematic research has been undertaken on frazil ice and there is quite a diversity of opinions in the literature concerning this subject, as can be seen from a review of the subject made by Williams.[1]

Two types of problems, with practical applications, are brought up by frazil ice. The first one is related to the quantity of frazil ice that can be produced and the second one is the problem of clogging of water passages in engineering works by this special type of ice.

Because of the fact that the ice ratio is small in a frazil ice pack, it takes a very small quantity of ice to occupy an important space in a river channel. Thus, frazil ice contributes in no small way to the obstruction of channels and to the formation of ice jams. The tremendous quantity of frazil ice that blocks nearly all the river channel in Montreal Harbor, during the winter, illustrates clearly this problem.

The most adverse effect of frazil ice is certainly its clogging of water passages in engineering works. Frazil ice has been known to clog partially and even completely trash racks of water intakes, wicket gates and even propeller blades of turbines. This problem is most felt in hydro or steam power plant because the advent of frazil ice coincides with the period of maximum load demand on the networks. A reduction in power production, at that critical time, becomes synonymous with a reduction of firm power that the plant can produce for the whole year. Where it occurs, the frazil ice problem becomes a major factor in the design of a power plant and it might cost millions and millions of dollars.

Description of the experimental ice flume

The ice flume used for the test on frazil ice was built outside in an open area of the Campus of Laval University, where it is well exposed to the cold predominant north and north-east wind, in winter.

As shown on Figure 1, it consists of an upper flume 22 feet long at the end of which a pipe returns the water, underneath, to an 8 inches propeller pump. This pump feeds the upper flume, the whole installation thus being a close water circuit.

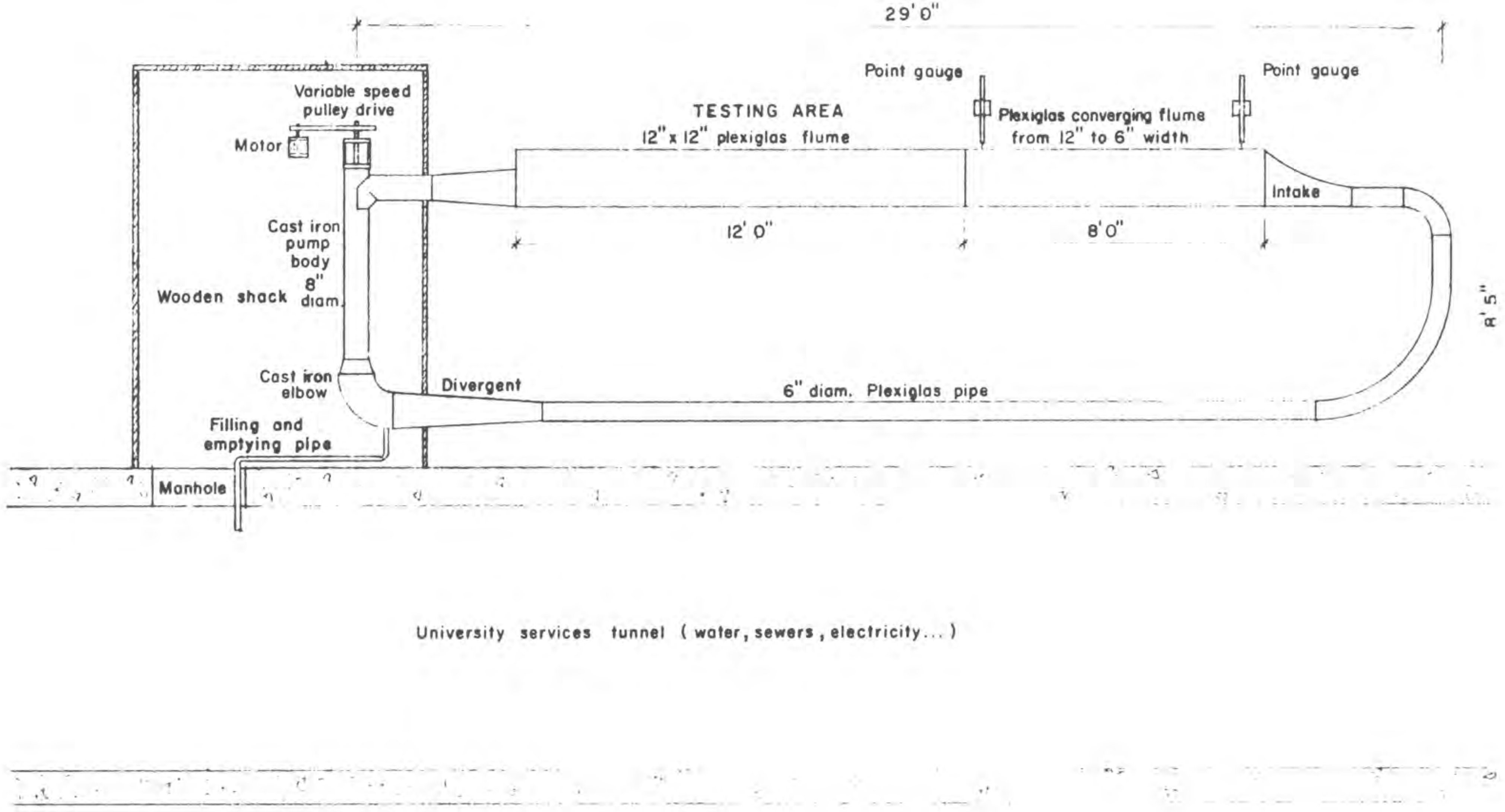

Fig. I — Experimental Frasil Ice Flume

The upper flume is the testing section of the experimental installation. It has a 12 inches by 12 inches section, 12 feet long, at the end of which the width converges to 6 in. before the water goes, in confined flow through a special intake, in a 6 in. diameter return pipe. This pipe leads to a vertical shaft 8 in. diameter pump which feeds the upper leg flume through a suitable transition.

The installation is built with plexiglass, to enable observations on frazil ice, except for the cast iron body of the pump.

The design of the circuit was as hydrodynamic as possible in order to offer a minimum of obstruction to the flow containing frazil ice. Of course the impeller and its shaft have to be inside this circuit.

The discharge is read by measuring the water levels at both ends of the converging section of the upper flume with point gages. The discharge is set by varying the rotating speed of the impeller with a variable speed pulley drive. These speeds of rotation could be set from 620 r.p.m. to 1800 r.p.m. giving discharges in the circuit varying from about 150 gal. per min. to 600 gal. per min. The possible range of water velocities in the 12 in. testing section of the flume was from about 0.5 ft per sec. to 1.8 ft per sec.

The experimental installation is set on the service tunnel of the University . The pump is enclosed in an unheated wooden shack inside of which a manhole gives access to all services inside the tunnel. The rig is filled with water from a 3/4 in. copper pipe coming from the service tunnel. At the beginning of each test, the initial temperature of water in the installation would be adjusted by mixing cold and warm water from the service tunnel.

The whole installation is 29 feet long and 8 feet 5 in. high and it is supported by a structure made of dexion steel angles. It was rapidly assembled. Problems of water tightness, caused by water making its way between joints and forming ice, have been severe during the whole period of operation of the ice flume.

Production of frazil ice

More than 80 tests, where frazil ice was produced, were made during the winters of 1961 and 1962. These tests were carried, mostly at night, with outside temperature ranging from -25°F. to +20°F. This latter temperature is about the highest limit where frazil ice could be produced in the flume because of the heat losses, at the pump and in the turbulent flow, that would prevent a lowering of the water temperature to the freezing point.

When it was not snowing, the mechanism of production of frazil ice was always the same, and can be illustrated with a typical test curve shown on Figure 2. The water temperature which is initially over zero degree centigrade cools down at a certain rate depending on outside atmospheric conditions. The rate of cooling is normally constant if it is considered during a short period of time; short enough so that the atmospheric conditions will not change. The temperature of water then attains 0°C and continued to drop a few hundreds of a degree below zero at the same rate. Then, the rate of cooling starts to diminish until it becomes quickly zero. At this point the temperature of water attains a minimum which was from -0.04° C to -0.08° C for all tests. As the rate of cooling starts to drop very small particles appear suddenly and quite uniformly in the whole mass of water. They are too small to be described with the naked eye but they are well seen at night by the reflection they give from an incident light. There frazil ice particles grow rapidly in size and form needle like fragments about 1/8 in. in length with very small dimensions on other sides. After the water temperature reaches a minimum it returns to zero degree with a high rate of temperature change at the start, followed by a continuously decreasing rate. This gives the temperature curve a more or less asymptotic appearance as it tends towards 0°C. During that period the individual particles agglomerate together and form foamy packs in water whose sizes depend on the turbulence and velocit of the flow. In our flume these travelling packs were from 2 in. to 6 in. in equivalent diameter and they were smallest at highest flow velocities. All this phenomenon occurs in 3 to 6 minutes after which the water temperature stays at 0°C and no more frazil particles of the type described above are produced. The packs of frazil ice follow a trajectory towards the surface of water in the upper flume, most of them floating on the surface. If the flume is allowed to run in that state for a long time it is most evident that all new ice that is produced either grows on the existing particles of the floating frazil ice packs or makes border ice that has a tendency to grow towards the center of the free surface and close it with a solid ice cover.

This type of test was made in various atmospheric conditions even under direct sun exposure at noon. It was even made with solid ice left on the walls and bottom of the flume with an initial water temperature above 0°C.

In all cases, the phenomenon was the same, although the quantity of frazil ice particles in water did not appear to be identical for each test.

When it is snowing, the processes of formation of the frazil particles is not so clear. There is also some undercooling but it is much less than it would normally be. Frazil particles do appear but they are mixed with the snow particles that have fallen in the cool water and have a tendency to agglomerate quickly to these snow particles.

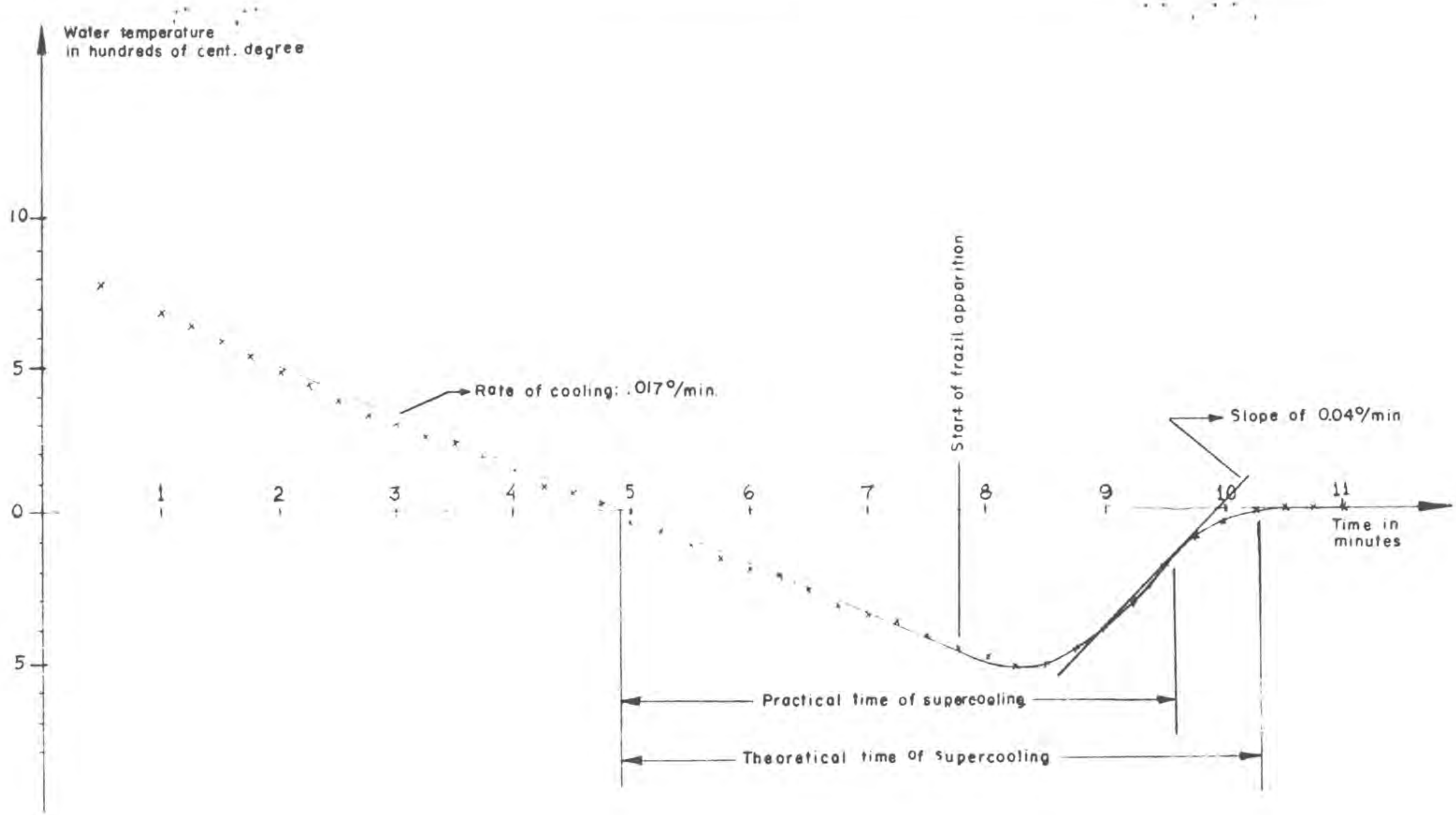

FIG II – Temperature of water during frazil ice production.
Test no. 27.

From these observations, giving similar results in all cases, some general rules could be derived concerning the formation of frazil ice. First of all it is most important to note that whatever be the rate of heat extraction from a body of turbulent water, once its temperature has settled to $0^{o}C$ the type of ice that is formed is physically very different from frazil ice formed during a supercooled period. Thus we think that the definition of frazil ice should be restricted only to the ice formed during the supercooling period. This definition will, in fact, be confirmed later when we will consider the particular properties of frazil ice. With this definition in mind, it can be said, very generally, that frazil ice is always and only formed if a body of turbulent water being initially above $0^{o}C$, is subject to a rate of cooling as its temperature reaches the value of $0^{o}C$. Frazil ice formation is essentially a transitory phenomenon because once it has formed the temperature of the body of water will remain at $0^{o}C$ and no more frazil ice will be added. The ice formed during such a limited period can be called a frazil ice run.

What is more peculiar about frazil ice is the fact that such a small quantity of ice produced in only a few minutes would occupy such an important space in water. This is indeed explained by the very high water ratio in frazil ice packs. Although we had no means of measuring this water ratio it was possible to make a rough estimate of the percentage of space occupied in our flume by the frazil packs of a frazil run. This was done by decreasing slowly the velocity in our circuit until the frazil packs would collect in a layer at the free surface of our flume. Visual estimates, for the conditions of the tests, showed that the space occupied by frazil ice packs was about from 2 to 10% of the total water volume. Further measurements have to be made to obtain better estimates of these important values.

The phenomenon of frazil ice production is much similar to the more general one of crystallization in a supersaturated medium. Unfortunately there does not appear to be any law to make quantitative prediction of crystal production in this general case. The literature on frazil ice seems to indicate that the quantity of ice that would be formed would depend on a number of variables including the presence of dust or foreign particles acting in water as nucleus for the formation of ice crystals. After consideration of the variables that could intervene in such a phenomenon we were able to arrive at definite preliminary conclusions concerning the amount of frazil ice that is produced in each frazil run. The results of the tests show that the correlation is good between the quantity of ice produced and the rate of cooling of water. It would thus appear, in the first approximation, that this latter variable is the only one which is important to determine the quantitative aspect of frazil ice production.

The amount of frazil ice that is produced in each frazil run can be computed theoretically from the temperature of water versus time curve of Figure 2. The rate of cooling of water, which depends on outside atmospheric conditions, is known from this curve as the water temperature goes through 0°C. It can normally be assumed that outside atmospheric conditions will vary little during the succeeding few minutes so that the rate of heat taken out per unit of weight of water is also known for the whole period of frazil ice production. The curve also shows the total amount of heat which was taken out to produce frazil ice is known. With the equivalent heat of fusion of water it is then an easy matter to determine the amount of frazil ice that is produced in a frazil run.

To use that simple method of computation the main difficulty arises when we have to determine the point at which frazil ice stops to form, because of the more or less asymptotic form of the temperature curve to the 0°C axis. A small variation of temperature along this curve will make an important change in the length of time of frazil ice production. Moreover, the temperature curve is accurate only within the precision of the thermometric system. In our tests we measured the temperatures of water every 15 sec. by visual observations on a Beckman differential thermometer and the accuracy of the readings were ± 0.0025°C. Considering the fact that the total range of temperatures of interest in the supercooling zone is only a few hundreds of a degree, this does not give a very good accuracy. To set a practical limit on the temperature curve that would indicate the end of frazil ice production, while giving small possible errors for all tests on the time ordinate, we came to the arbitrary decision of using the point for which the rate of heating of the supercooled water was 0.04° C per min.

The results of all the tests interpreted in this manner are shown on Figure 3. It can be seen that there is a good correlation between the quantity of ice produced in pounds of ice per pound of water in function of the rate of cooling of water at 0°C. This quantity of ice increases with the rate of cooling. These tests were made with flow velocities varying from 0.7 ft per sec. to 1.8 ft per sec. in the upper flume. No care was taken concerning the presence of foreign particles in water; sometimes the water was very dirty, other times it was not. These factors do not seem to influence, in the first approximation, the quantity of ice that is produced in a frazil run.

These results could be used to predict the quantity of frazil ice that can be produced in a frazil run. It is remarkable that such small percentage of ice in water occupy such an important space when the frazil particles form ice packs. For a production of 0.001 lb of ice per lb of water and an average relative volume of the packs of 5%, the ice ratio by weight would be only 2% in the ice packs. This small percentage of ice in frazil ice packs explains their important contribution to ice jams in rivers.

Deposits of frazil ice

The main problem of frazil ice is its property to adhere strongly to objects that come in contact with it in a flowing stream.

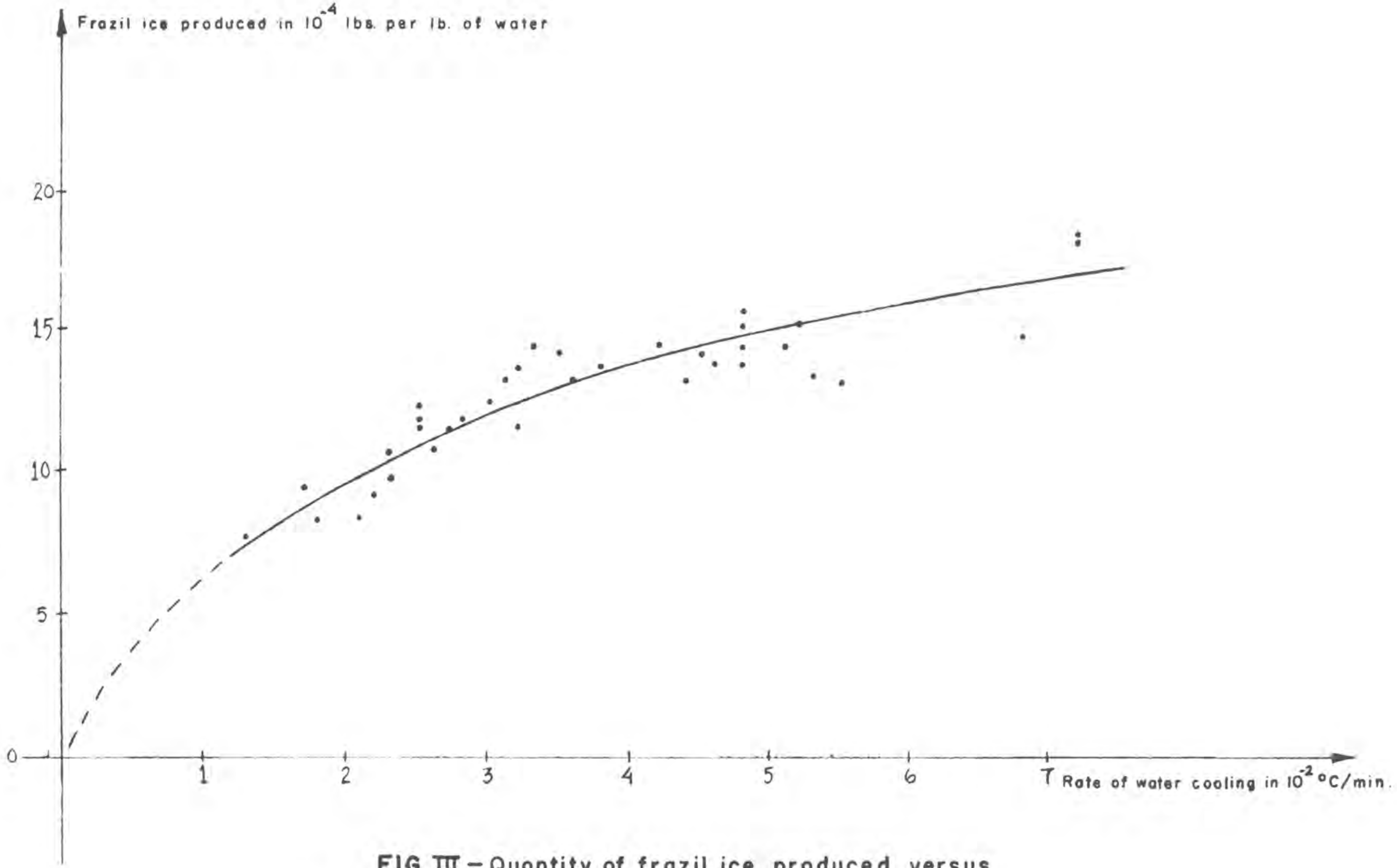

FIG III – Quantity of frazil ice produced versus rate of water cooling

This problem of adherence might be studied under various angles. We might ask ourselves the following questions: "Where, when and how does frazil ice adhere to an object?", "Does it stick to any type of material?", "What is the growth of the deposits and what factor do affect this growth?" These are some of the questions we tried to answer with our experimental frazil flume.

If frazil ice is so sticky, it would immediately adhere to the walls of the flume. But right at the first tests, and for all of them, we could not observe any deposit on the walls of our plexiglass flume in rectilinear sections. As said previously, the frazil particles would agglomerate in foamy packs, after their formation, and travel on and on in our closed circuit. After a long operation of the flume, with a frazil run, one whole night for instance, we would observe the following things:

- Small and disseminate ice flakes on the straight parts of the plexiglass walls and on the return plexiglass pipe. This type of ice formation could easily be explained because of the cooler temperature of the walls exposed to outside conditions.

- Formation of a partial or total solid ice cover in the flume with an important deposit of frazil packs underneath. In some cases all the packs would be deposited.

- Small deposits of frazil packs in no-flow zones in the circuit, where separation would occur. This would be the case at the junction of the confined and free-surface flow and in lower corners of the rectangular flume. In that case, frazil ice would tend only to shape a better hydrodynamic water circuit.

From these results it became evident to us that frazil ice would not deposit on any type of material because it did not adhere to the plexiglass walls after lengthy operation. In fact we were lucky to have built a flume with such a material that enabled us to circulate frazil ice for a long time and keep it in suspension. But this reasoning just did not seem to apply to the bronze impeller and the cast iron body of the pump, inside which we could not make any observation. These materials are well known, in practice, to be subject to frazil ice deposit and, at this stage, we could not explain why the frazil packs would travel on and on in the circuit without adhering to these areas of the rig.

With these observations in mind our next step, in these experiments, was to put objects made of various materials in the flume during frazil ice formation and to observe the deposits on these objects. In order to make systematic observations we always used cylindrical rods, $\frac{1}{4}$ in. in diameter, that were set in the testing area of the upper flume. We used brass, steel and concrete made rods.

For 29 tests with the naked brass rods, four of them under direct sun exposure at noon, there always were a deposit on the rod. To make sure that this adherence would not be caused by the fact that the rod itself would be cooler than 0°C, as part of it was left outside of water, we made a special isolating plexiglass support so that the brass part of the rod was completely submerged in water. The deposits were identical.

For 19 tests with the naked steel rod, many of them during daytime, frazil deposits occurred 18 times. The only exception happened under direct sun exposure with part of the steel rod outside of water. It might have been that the rod was thus heated by radiation a fraction of a degree above 0°C.

For 24 tests with the concrete rod there never were any deposit.

Finally we made 14 tests with the steel and brass rods covered with different types of plastic coatings. We used tygon, talypon and an acrylic resin. For those tests, also, there was not any deposit on the rods.

The conclusion of these tests are simple and have far reaching consequences. They confirm an important observation made by Piotrovich.[2] Frazil ice does not stick on certain types of material such as concrete or plastics. Trash racks or other objects in flowing water which are susceptible to come in contact with frazil ice, can be coated with plastic paints to eliminate the danger of frazil ice sticking to them.

Up to now we have said nothing on the processes of deposit of the frazil particle on the steel and brass rods. At the apparition of the individual small frazil particles in water, a thin layer of ice crystals would appear all around the rod. Then the deposit would grow in the wake of the rod forming an extending blade behind it. It would hardly progress in front of the ro At the beginning the rate of progression of the ice blade behind the rod would be fast but it will decrease as time goes on and would stop completely in a few minutes; the deposit attaining a length of 3 to 4 inches. During the first tests we thought that the equilibrium reached depended on the velocity of the flow but, accidentally, we put a steel rod in water some minutes after the frazil run had begun when the frazil packs were still moving in water. To our surprise there was not any deposit on the steel rod. This test was made again and again. We would for instance shake out rigourously the deposit on a steel rod after equilibrium was reached, leaving the rod under water, and no more deposit would occur.

The explanation confirms the whole processes of frazil ice formation After the temperature of water in a frazil ice run returns to 0° centigrade th is no more potential of frazil ice growth either for a separate particle, for particles agglomerating together and forming frazil ice packs, or for frazil particles growing on foreign crystals. Thus frazil ice becomes inoffensive an unable to grow on other particles. We might call this frazil ice, inactive frazil; its processus of formation has been completed and its properties are n more different in water than slush made by snow falling in it.

This phenomenon also explains why frazil ice would not completely deposit on the cast iron body of the pump. Frazil ice is active only a very few minutes after the start of its apparition in water. Only some particles can, during that short time, come in contact with the impeller and wall of the pump and the deposit is partial. That is why inactive frazil ice packs can continue to travel a very long time without depositing in that section of our flume.

Because of the fact that in a closed circuit flume you cannot have a continuous source of active frazil ice, as might happen at the foot of a rapid in nature, it is not possible to experiment the growth of frazil ice deposit with our experimental installation.

Conclusions

Tests carried on in an experimental flume set outside on the Campus of Laval University were aimed at getting information on the formation and properties of frazil ice.

They enable us to formulate fundamental laws concerning this type of ice which are:

-Frazil ice is always formed if a body of flowing water in a turbulent state, whose initial temperature is above 0° centigrade, is subject to a rate of cooling as its temperature attains the zero degree limit. These conditions appear to be necessary. No frazil ice is ever formed if the flow is laminar, if the initial temperature of water is zero degree, whatever be the rate of heat extraction, or if the water temperature attains zero degree in an asymptotical fashion. These conditions are also sufficient for the formation of frazil ice. It will form under direct sun exposure and even in the presence of unmelted ice in the flowing water.

-Frazil ice formation is a transitory phenomenon in a given body of water. After the supercooled body of water has produced frazil ice and its temperature has returned to 0° C no more ice of that type is formed. Further heat extraction on the water would produce normal crystal growth on existing ice particles. Frazil ice can only be defined as the type of ice which is produced during the period of supercooling of a body. The frazil ice which is produced in limited quantity during one of those transitory periods can be called a frazil ice run.

-Our tests show that there is a good correlation, as a first approximation, between the quantity of frazil ice produced in a frazil ice run and the rate of cooling of water at $0^{o}C$. Quantitative results were obtained for a good range of rates of water cooling.

-As related to its main property of adherence to foreign bodies, frazil ice can be called active or inactive. The active state occurs only during the period of formation of frazil ice when the water is supercooled. During that period there is a potential for growth of the ice particles. Particles coming in contact with other particles or with foreign material of favorable crystalline structure will group togethe to make a more complex formation. Foamy ice packs with a high water ratio will be formed and frazil will stick to certain objects made of material such as steel, brass, etc... It will also grow directly on snow nucleus that might have fallen in water at that time. In the inactive state, after the water temperature would have returned to 0°C frazil would normally be present in foamy packs but will not have a tendency to grow on objects and cling hard to them. They will deposit in separated no-flow areas of the hydraulic circuit. Because of their asperities the packs will cling under an ice cover to be later soldere to it by the cover growth underneath.

-Finally many types of material will not permit the growth of active frazil ice crystals on their own crystalline structure. The most important of these materials is the class of amorphous plastics.

These fundamental results have wide consequences to solve most of the engineering problems brought up by the clogging of water works with fraz ice. Careful design of these works, with them in mind, would eliminate fraz ice problems in most cases without having to have recourse, before or after to costly or temporary solutions.

We wish to acknowledge the contribution of the National Research Council of Canada who made funds available for this study.

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1 - Williams, G.P. - Frazil Ice. A review of its Properties with a selected bibliography. Eng. Journal - Vol. 42, No. 11, November 1959.

2 - Piotrovich, V.V. - Formation of Depth ice. Priroda- Vol. 9, 1956 pp. 94-95.

THEORY OF FORMATION AND DEPOSIT OF FRAZIL ICE

Discussion by E. Pariset, Vice-President,
Lasalle Hydraulic Laboratory Ltd.
and
R. Hausser, Chief Engineer,
Lasalle Hydraulic Laboratory Ltd.

We are doubly pleased to compliment Dr. Michel firstly and mainly for his excellent work and secondly because Dr. Michel began to work on ice problems when in our Lasalle Laboratory.

Dr. Michel gives a very clear picture of frazil ice formation: very small particles which appear suddenly and uniformely in the whole mass of super-cooled water. Such a phenomenon is of course quite difficult to visualize in the field.

We are pleased to note that the size of frazil particles as seen, seems in general agreement with the size as derived from calculations we have done from general laws of suspension to analyse shape and amount of frazil deposit under the Beauharnois Canal.

The results presented by the author are of great interest, however their comparison with other results of field measurements show some divergencies which would require a certain amount of explanation.

a) Let us begin with the minimum temperature of the super-cooled water. Mr. F. I. Bydine* had found from measurements in rivers of Russia, that this temperature is obviously 0°c for very slow flow velocity; that it attains value of -0.005 to -0.01°c for velocities of about 2 f/s and that it can become -0,02°c for larger velocities.

   These figures are quite smaller than -0.04 to -0.08°c reported by Mr. Michel for all his tests.

   These discrepancies could be due either to the agitation or the heating effects of the circulating pump which disturbs the molecule arrangement of the super-cooled particles of water, preventing them from freezing as long as the water temperature is not low enough. It would therefore be a local condition obtained by the particular experiment.

b) We do not agree with the author, except if there is no flow velocity, when he states that there is no more frazil in formation after the super-cooled water has returned to 0°c.

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* Dynamics of water streams by I.I. Levy
Edition of Energy Development (1948).

We think, rather, that frazil ice formation keeps on, may be at a lower rate which corresponds to the free travel of the super-cooled water particles before meeting an ice crystal or another nuclei which prime their freezing. When the frazil ice concentration increases, the free travel of the super-cooled water particles decreases, and the main body of water temperature tends towards $0^{o}c$, but probably without reaching it accurately, as shown by the asymptotical shape of the temperature curve.

c) On the subject of the property of adherence of frazil ice, we think that in fact it is not the frazil ice itself which sticks on bodies, but rather the super-cooled water particles which crystalize on solid bodies as soon as they reach them.

That hypothesis could explain why in the experimental flume there is not any more frazil ice deposit on the foreign bodies after the water temperature has returned to $0^{o}c$. At this stage the concentration in frazil ice is indeed becoming such in the experimental flume, that the super-cooled water particles can not anymore reach the submerged bodies without having already found ice particles on which they crystallize.

d) Going on with the adherence properties of frazil ice, we ourselves did a lot of tests, but we never succeeded in finding a material on which the frazil ice did not adhere. These tests, carried out in 7 feet diameter pipes of the City of Montreal Water Intake have shown that after a travel of 2200 feet in the submerged pipes, at a flow velocity ranging from 2.5 to 3.5 feet/second, the frazil ice is still able to adhere very well on various kinds of material even on polythene wires $\frac{1}{4}$ inch in diameter.

In all cases the frazil ice deposits appeared only in the disturbed flow areas, where the deposits tend to build better hydrodynamic shapes as mentioned by Mr. Michel.

Except on the upstream edge, there is no frazil ice deposit on flat sheets or rods submerged in a direction parallel to the flow.

Similar deposits occurs on the upstream edge of a sheet of cement-asbestos. In this latter case, the deposits which can be seen on the sheet are caused by the protruding head of the fixing bolts.

The phenomenon which prevents deposits on surface parallel to the flow can explain the reason for which Mr. Michel did not find deposits on the rectilinear wall of his flume.

In conclusion we must say, that during our tests on the City of Montreal Water Intake, deposit patches of frazil ice were found on all protuberant asperities and joints of the concrete pipes.

e) As to the ratio of ice in packed frazil ice, the very small value (2 % in weight) found by Mr. Michel can easily be explained by the very small forces acting to compact the frazil deposit in the experimental flume. For this reason we do not think that the results can be used for design purposes, as in nature the pressure forces are much larger and their compaction effects on the packed frazil ice must give a much larger ratio.

We want to congratulate Dr. Michel for his so interesting work, however we think that many tests and studies are still needed to give the problems involved by the formation and the behavior of the frazil ice, and arrive at proved conclusions.

Discussion by J.E. Cousineau, P.E., Technical Services Engineer,

Quebec Hydro-Electric Commission

Doctor Michel's experiments constitute quite an approach to a clearer definition of frazil ice and to a better understanding of the mechanism of its formation. The conditions under which this type of ice forms, its quantitative analysis and its fundamental property of adhering to a certain substances have thus been repeatedly experimented.

In nature, I have often observed that frazil formation always occurs throughout the turbulent flow in an open channel. Wind and wave action will also cause some formation of frazil ice at the surface only, of a laminar flow. During a cold spell, the water appears dull in color, as if mixed with fine sand. An inspection under sunlight of a sample of this mixture, taken with a glass, disclosed the presence of numerous fine crystals. In a cold atmosphere, water, placed in a tub and stirred rapidly, yielded frazil that soon turned to what Doctor Michel refered to as foamy packs, by the agglomeration of these fine crystals. This, for those who may wish to manufacture frazil in their own backyard.

The rate of formation of frazil ice, on a bright, sunny and very cold day, always seemed to be lower than that of frazil ice formed at night, under a clear sky, at about the same atmospheric temperature.

The source of frazil ice is continuous for power plants fed with a turbulent flow. It is this type of ice in particular which causes an open channel to be of so much trouble to power plant operators. Frazil may cause obstruction to free flow of water by adhering to the racks and gradually closing them completely. Even with racks lifted to prevent their clogging, plants can be and are known to have been partly shut down by frazil ice adhering to and clogging the water passages to the turbines.

The results of Dr. Michel's tests point out wide practical values, more especially that of designing power developments supplied either directly from reservoirs or from canals and rivers having a large cross-sectional area. On streams that are cooled down to the freezing point, a laminar flow will allow the formation of a smooth ice cover that will provide power plants with the best protection against ice troubles. A continuous ice sheet over a forebay will put a stop to the generation of ice of all types, save of course for the growth of the cover itself.

Experience to this day has shown that, frazil ice cannot be dispose of simply by letting it run through a plant. As it is claimed that some typ of materials will not permit adherence of frazil ice crystals to their own crystalline structure, a wide field may be open to technical research which, I hope, may bring about, some day, a solution to the frazil ice problem that would undoubtedly result in more economical designs of power plants.

THEORY OF FORMATION AND DEPOSIT OF FRAZIL ICE

Discussion closure by B. Michel

The writer appreciates the interesting discussions of Messrs. Cousineau, Pariset and Hausser. Both discussions brought observations concerning frazil ice in nature and this is indeed important for the extrapolation of our fundamental results.

Messrs. Pariset and Hausser say that there are certain divergences between our results and observations in nature. We do not see where, by taking into account the facts they have given in their discussion.

The minimum temperature of supercooling of water in our flume was higher than normally believed to be in nature simply because we operated for much higher rates of water cooling than is usually found in nature. Since those tests were made we worked with lower rates of water cooling and obtained minimum temperatures of supercooling of the order of -0.01°c and -0.02°c.

Messrs. Pariset and Hausser did a lot of tests in nature and they say that they were never able to succeed in finding a material on which frazil ice did not adhere. I believe they did not understand completely the laws of deposit and adherence of frazil ice, as stated in our paper and it might be interesting to repeat them here to clear this point:

- In the active state (when the water is supercooled) there is a potential for growth of the ice particles. Particles coming in contact with other particles or with foreign material of favorable crystalline structure will group together to make a more complex formation. Many types of material (plastics ...) will not permit the growth of active frazil ice on their own cristalline structure.

- In the inactive state (water at 0°c) frazil would be present in foamy packs but will not have a tendency to grow on objects and cling hard to them. They will deposit in separated no-flow areas of the hydraulic circuit.

Many examples of this second case, and clearly described as thus, were brought up by the discussers. It is most evident in that case, that whatever be the material forming the boundary of the no-flow area (we had plexiglass in our flume) frazil will deposit to form a better hydrodynamic circuit as we stated, and was repeated by the discussers for their own tests.

The deposit of inactive frazil ice in no-flow areas can not be taken to prove that frazil ice will grow on objects made of any material. Hard growth of crystals on an object and retention of loose crystals into separated areas of the flow about this object are quite different phenomena that we had clearly distinguished. From a practical point of view the former in which a better hydraulic circuit is shaped cannot be dangerous but the latter, where you built strong ice on an object can really be quite a problem.

Messrs. Pariset and Hausser also brought up interesting and ingenious hypothesis concerning the temperature of water always being under 0°c in an opened flowing stream containing frazil ice and concerning the mechanism of sticking of supercooled water particles. They finally say that the ratio of ice we gave, as a rough approximation, in packed frazil ice, cannot be taken for design purposes. We agree with their reasoning. We gave that figure with due reservations in our text, its main advantage was of being the first one to be ever published (thus being better than none at all).

Mr. Cousineau has pointed out one of the most important practical aspect of frazil ice in nature in saying that the source of frazil ice can be continuous for power plants fed with a turbulent flow. This would certainly be the case at the foot of a rapid in nature. The head losses would first heat the water above 0°C in the rapids and the water would then cool down in the forebay to form frazil ice. It might happen that the supercooled water would be present at the intake to the structures and a continuous supply of dangerous active frazil ice would occur at the wrong place.