SIZE DISTRIBUTION OF FRAZIL FLOCS

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ABSTRACT

Laboratory experiments were conducted to study the formation and evolution of frazil from a Lagrangian frame of reference under different simulated turbulence conditions. The experiments were conducted in a circular flume in which the flow was created and sustained by moving the bottom. Frazil concentrations were measured at three depths with a patented frazil instrument. Frequency density versus non-dimensional floc length histograms were determined from the data. The histograms showed skewed distribution of the flocs to the shorter end. The majority of flocs were shorter than twice the flow depth. Flocs 6 to 8 times the flow depth would be considered long flocs and rarely would flocs be longer than ten times the flow depth. The different frazil floc characteristics at different depths could be accounted for by the nature of turbulence in the flow and the agglomerations process of frazil.

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INTRODUCTION

When the temperature of a turbulent flow reaches the freezing point, frazil crystals will form uniformly in the slightly supercooled water. Following their formation, the frazil crystals will grow and at the same time adhere to each other to form clusters and flocs. On the other hand, the turbulence of flow will break up the agglomerations formed. However, the tumbling action of the flocs in the flow tends to compact the flocs. At equilibrium, a certain size distribution of the frazil flocs will be established. This size distribution is dynamic. As more frazil is produced in the water and the hydro-thermal history of the frazil changes with time, new equilibrium states will be reached. At the final stage of frazil evolution, the frazil will agglomerate into large packs that will respond to or be affected by only the large eddies of flow turbulence. These large frazil packs rise to the surface to accumulate into a surface slush layer. Freezing of the surface slush layer leads to pancake ice and frazil floes.

This paper reports a laboratory study in which the size distribution of frazil flocs at different stages of frazil evolution was measured. Knowledge of the size distribution of frazil flocs will help the basic understanding of the evolution process of frazil in rivers.

The distribution of frazil in a frazil floc is not uniform. If a frazil floc is defined as a mass of water/frazil mixture whose frazil concentration is greater than zero, a dense floc may be defined as an agglomeration, or the part of an agglomeration, whose frazil concentration is greater than a certain given value. In this laboratory study, the size distribution of dense flocs was also measured and will be reported.

EXPERIMENTAL APPROACH AND SETUP

The cooling of water and the formation and evolution of frazil may be studied from a Lagrangian frame of reference by following an identified parcel of water as it drifts downstream. In the laboratory, the water flowing in a circular flume may be used to simulate the identified parcel of water. Details of the physical reasoning for arriving at such an simulation are shown in a progress report by Tsang (1989). To generate a flow in the circular flume, one may move the bottom. As the bottom moves, it drags the water to move with it. At equilibrium, a velocity profile will be established with a progressively decreasing velocity with distance from the bottom. This velocity profile is the absolute velocity profile. To an observer sitting on and moving with the bottom, he will see water flowing in the opposite direction at a velocity equal to the difference between the bottom velocity and the absolute velocity. This velocity profile is the relative velocity profile. It is the relative velocity profile that controls the flow turbulence and simulates the flow in a river.

A circular flume with a trough of measuring 0.123 m wide and 0.254 m high (6"x10") was constructed. The diameter of the centre-line of the flume was 1.0 m. An annular ring driven by a variable speed motor served as the moving bottom. 2 mm gravel with a hydraulic roughness of 1.68 cm was laid on the bottom to provide bottom roughness. Different relative bottom roughnesses were obtained by changing the flow depth. The flume was placed in a cold room. To restrict cooling to the surface only and to prevent icing on the side walls, the flume was imbedded in a heated insulated enclosure. The temperature inside the enclosure was maintained at a temperature slightly above freezing. For further information on the experimental apparatus, one may refer to the progress reports by Tsang (1989, 1990).

FRAZIL INSTRUMENT AND MEASUREMENT

A frazil instrument based on the patented design by Tsang (1985) was constructed to measure frazil concentration in water. The instrument had three sensor probes and could measure frazil concentrations simultaneously at three points. For the experiments, the three probes were immersed at different depths. Three frazil voltage signals were produced by the sensors. They were converted into digital form through a data acquisition system and recorded on computer for later analysis. Further information on the frazil instrument and the data acquisition system was reported by Tsang (1989, 1990).

EXPERIMENTS

Back-ground experiments were first conducted under ice-free conditions to establish the relationship between the rotating speed of the bottom and the relative velocity of the flow under different flow depth conditions. Conventional current meters were used to measure the flow velocity. While they performed well under ice-free conditions, all failed in a frazil-laden flow because of ice blocking and clogging. Pre-ice velocities, therefore, were used to specified the hydraulic parameters of the experiment.

Water temperature was measured with a precision thermometer with a resolution of 0.002 ^{0}C. From the water temperature measurements, the cooling rate of water before ice production was obtained. This cooling rate was assumed to remain the same through out the experiment.

A total of three experiments were conducted to investigate the size distribution of frazil flocs. The parameters of the experiments are summarized and shown in Table 1:

Table 1: Summary of Experiments.

Exp.	h cm	Ve cm/s	Re $x10^4$	e/h	dT/dt $.001^0C/min$	$\Sigma\Delta t$ s	z*a	z*b	z*c
I	18	17.7	1.776	.093	5.0	4800	.833	.667	.333
II	18	26.2	2.628	.093	9.2	4800	.833	.700	.334
III	12	18.0	1.200	.140	7.2	7800	.750	.583	.417

Notes: h = Depth of flow.

Ve = Relative velocity.

Re = Reynolds number based on Ve.

e, e/h = Absolute and relative roughness of the bottom respectively.

dT/dt = Cooling rate of water.

$\Sigma\Delta t$ = Duration of experiment.

z*a, z*b, z*c = Height of immersed probes from the bottom, normalized on flow depth h. Subscripts a, b and c indicate the top to bottom order.

The turbulence level of the above experiments was in the increasing order. For Experiments I and II, the increasing turbulence can be see from the increasing Reynolds number because the relative bottom roughness was the same. For Experiment III, the high turbulence was caused by the high relative bottom roughness which outweighed the reduction in Reynolds number.

A probe of the frazil instrument was composed of two metal disks imbedded in plastic shells a distance apart, where a cylindrical volume of water, 22 mm dia. x 22 mm was continuously monitored. Because of the finite size of the probes, the smallest depth of immersion at the top without introducing surface ripple effect was 30 mm. In Table 1, the top normalized depths all represent such an actual depth.

DATA AND DATA ANALYSIS

Fig. 1 is an example of the frazil concentration voltage signals obtained from Exp. III. Three frazil voltage signatures were obtained by the three sensor probes immersed to different depths. From the signatures, the fast reduction of frazil presence with depth is immediately evident. It may be noted that the vertical scale of the *plottings increases from top to bottom to exaggerate the* signals at the lower depths. The voltage signals could be converted to frazil concentration signals for the probes through relationships established through calibration experiments. These relationships are shown above the signatures in Fig. 1. They are approximately linear and close to each other. The small deviance among the relationships was caused by manufacturing tolerance of the probes when they were constructed. It was the concentration data that were stored in the data bank for later analysis. From these stored data, concentration versus time signatures similar to those in Fig. 1 could be plotted.

In Fig. 1, the baseline of the concentration voltage signatures was off-set to above the V=0 volt line. This permitted observation of the meandering of the baseline, which was caused by electronic instability of the instrument and change in salinity of the water as ice was formed and salts were rejected in it. During the voltage to concentration conversion, the off-setting effect of the baselines was corrected.

From the meandering voltage signal baselines in Fig. 1, the maximum baseline drift for the frazil concentration signatures for the shown period was found to be about 0.05 percent. Over the entire experimental period, it was about 0.1 percent. As a whole, 0.1 percent was considered to be the resolution threshold and accuracy limit of the instrument.

For a concentration signature, if a horizontal line defining a reference concentration $C_i=(C_i)_{ref}$ was drawn, it would intersect the concentration signature at a multitude of points which defined flocs whose concentration was greater than $(C_i)_{ref}$. If $(C_i)_{ref}$ was close to zero, then all the flocs in the flow, thin or thick, would be identified. With such information, it then became possible to investigate the size distribution of all the identified frazil flocs. $(C_i)_{ref}=0$ was a singular case, in which the $C_i=(C_i)_{ref}$ line became the baseline. It only touched or coincided with, but did not intersect the signature so that the identification of frazil flocs by intersecting points became academic. Because of this reason, a small value of $(C_i)_{ref}=0.2$ percent was used to define "all" the flocs.

Fig. 1 shows that both the signal intensity and the signal frequency for the lower probe were low and would not justify a statistical analysis of the data. For this reason, frazil data obtained at the lower point were not included in the analysis.

When the $C_i=(C_i)_{ref}$ line cuts a signal spike at its base at two points, the intersecting points will identify the beginning and the end of the floc the spike represents. If the time interval between the two points is Δt, then the length of the floc will be $L=V_a\Delta t$, where V_a is the absolute velocity of the flow. The absolute flow velocity was used because all the probes were fixed to the ground. The floc

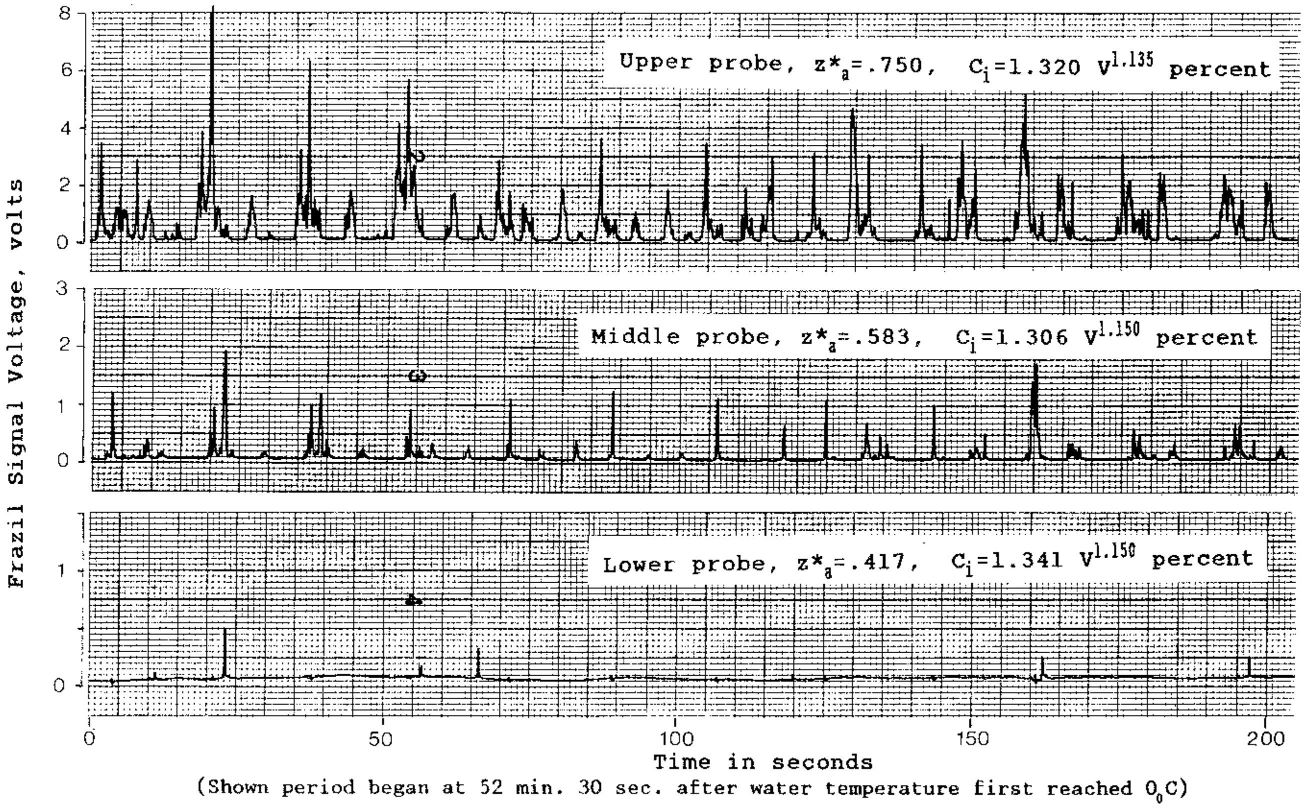

Fig. 1. Frazil concentration voltage Signature, Exp. III.

length L is an invariant, i.e., the same to an observer standing on the ground or an observer moving with the bottom. In the analysis, the floc length was non-dimensionalized by normalizing on the flow depth h, i.e.,

$$L^* = V_a \Delta t/h \qquad (1)$$

L*, therefore, expresses the floc length as multiples of the flow depth.

The likelihood of existence of a frazil floc of normalized length L* is given by its density function, or frequency density function f(L*), defined by

$$\int_0^\infty f(L^*)\, dL^* = 1 \qquad (2)$$

Physically speaking, besides being a function of L*, f(L*) should also be affected by the hydro-thermal history of the frazil.

The hydro-thermal history of frazil is nothing more than the accumulated effect of the thermal and hydraulic parameters on the evolution of frazil. In the present study, the thermal parameter was the cooling rate of water dT/dt. The hydraulic parameters were the flow Reynolds number Re and the relative roughness of the boundary e/h, which determined the turbulence characteristics of the flow. The accumulative effect was accounted for by the time lapsed from the time when the freezing point was first reached $(t-t_0)$. By non-dimensionalizing $(t-t_0)$ according to

$$t^* = \frac{C_w(dT/dt)(t - t_0)}{H_L} \qquad (3)$$

where C_w is the specific heat of water, and H_L is the latent heat of fusion of ice, one sees that the two parameters dT/dt and $(t-t_0)$ are now combined into one. This reduces the number of parameters from the original four to three, namely Re, e/h and t*. Because the numerator on the right hand side of Eq. 3 represents the total heat loss by a unit mass of water in the flume, t*, therefore, stands for the fraction of ice formed in that water mass, or in the flume as a whole.

EXPERIMENTAL RESULTS AND DISCUSSIONS

From the experimental data, size distributions of frazil flocs at different times were calculated for the three experiments. The distributions measured at the upper sensing point for $(C_i)_{ref}=0.2$ percent are shown in Fig. 2. As discussed earlier, this reference concentration should give "all" the detectable flocs.

Floc size distributions for Exp. I at different times are shown by the histograms at the top of Fig. 2. According to the definition of frequency density function (Eq. 2), the areas under all histograms should be the same and equal to unity. It is seen from the first histogram that at time $t^*=0.14\times10^{-2}$, or at the time when the average content of ice in the water was 0.14 percent, most the frazil flocs were shorter than 4 times the flow depth. The shorter the flocs, the higher was their frequency density. As time progressed, longer flocs began to evolve as could be seen by the increasing density function values for longer flocs. At $t^*=0.41\times10^{-2}$, many flocs of normalized lengths in the range of L*=4 to 8 appeared in the flow. The longest floc length measured was 14 times the flow depth. At t*=.50 (From now on, the unit 10^{-2} will be omitted for simplicity), flocs as long as 19 times the flow depth were seen. As a whole, however, the flocs were

$(C_i)_{ref}$ = .2 percent;   Turbulence level increased from Exp. I to III.

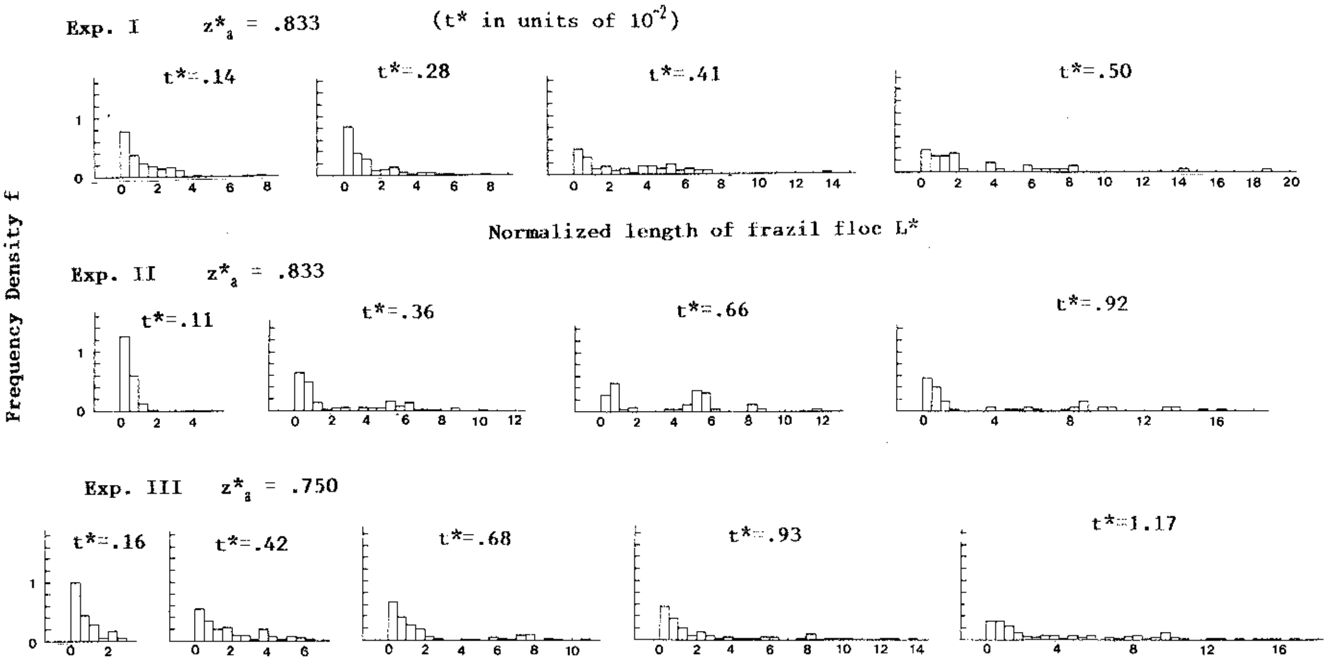

Fig. 2.   Size Distribution of Frazil Flocs Near the Surface at Different Times.

dominated by shorter ones. Even at the late stage, few flocs would be longer than $L^*=8$.

The middle histograms in Fig. 2 were from Exp. II, whose turbulence level was higher than that of Exp. I because of the higher Reynolds number and the same relative boundary roughness. From comparing the histograms of Exp. I and Exp. II, one sees that the stronger turbulence in Exp. II led to shorter flocs. At $t^*=0.66$, the longest flocs only had a normalized length of $L^*=12$, compared with $L^*=19$ at $t^*=0.50$ for Exp. I. Even at $t^*=0.92$, the longest flocs in Exp. II were only 16.5 times the flow depth, still less than the $L^*=19$ at $t^*=0.5$ for Exp. I, despite an increase in evolution time by more than 80 percent. In addition to the case of the longest flocs, the mid-length flocs in Exp. II also hovered over a lower L^* range than that in Exp. I for the same normalized times.

The same observations can again be said of the histograms of Exp. III which are shown at the bottom of Fig. 2. Although the Reynolds number of Exp. II was less than that of Exp. II, its relative boundary roughness was higher. The increase in relative boundary roughness greatly outweighed the reduction in Reynolds number in contributing to intensify the turbulence level of the flow. The highly turbulent flow in Exp. III also appeared to have led to a more smoothly varied density function as shown by the more continuous and slower changing histograms.

Although Fig. 2 shows a high portion of shorter flocs, this should not lead to the false impression that the "presence" of frazil in the flow was dominated by them. The presence of frazil by flocs in the range of L^*_1 to L^*_2 is given by

$$\int_{L^*_1}^{L^*_2} f(L^*)L^*dL^* \qquad (4)$$

which is the first moment of the density function about the vertical axis ($L^*=0$). The fractional presence is given by

$$P^* = \frac{\int_{L^*_1}^{L^*_2} f(L^*)L^*dL^*}{\int_0^{\infty} f(L^*)L^*dL^*} \qquad (5)$$

From the above equation and Fig. 2, one sees that at large L^* values, although the integration in the numerator on the right would decrease with reducing f values, it also would, on the other hand, increase with the increasing L^*. The longer flocs, therefore, would have a greater impact on the fractional presence of frazil in the flow. The production of corresponding histograms for P^* from Fig. 2 would be straight forward. However, it will not be presented here because of length limitation of the paper.

For the middle sensing positions, size distribution histograms (for $(C_i)_{ref}=0.2$ percent) for the three experiments are shown in Fig. 3. Comparing Fig. 3 with Fig. 2, one sees that at the lower depth, the frazil flocs were shorter and the distributions were more skewed to the shorter end. As an example, for Exp. I at $t^*=0.41$, although at the upper measuring point frazil flocs as long as $L^*=14$ were detected and many flocs existed in the range of $L^*=2$ to 8, at the lower depth, no floc longer than $L^*=3$ existed and nearly all the flocs were in the length range of $L^*=0$ to 2. The same observations could be said for all the other histograms, although the differences might not be as obvious.

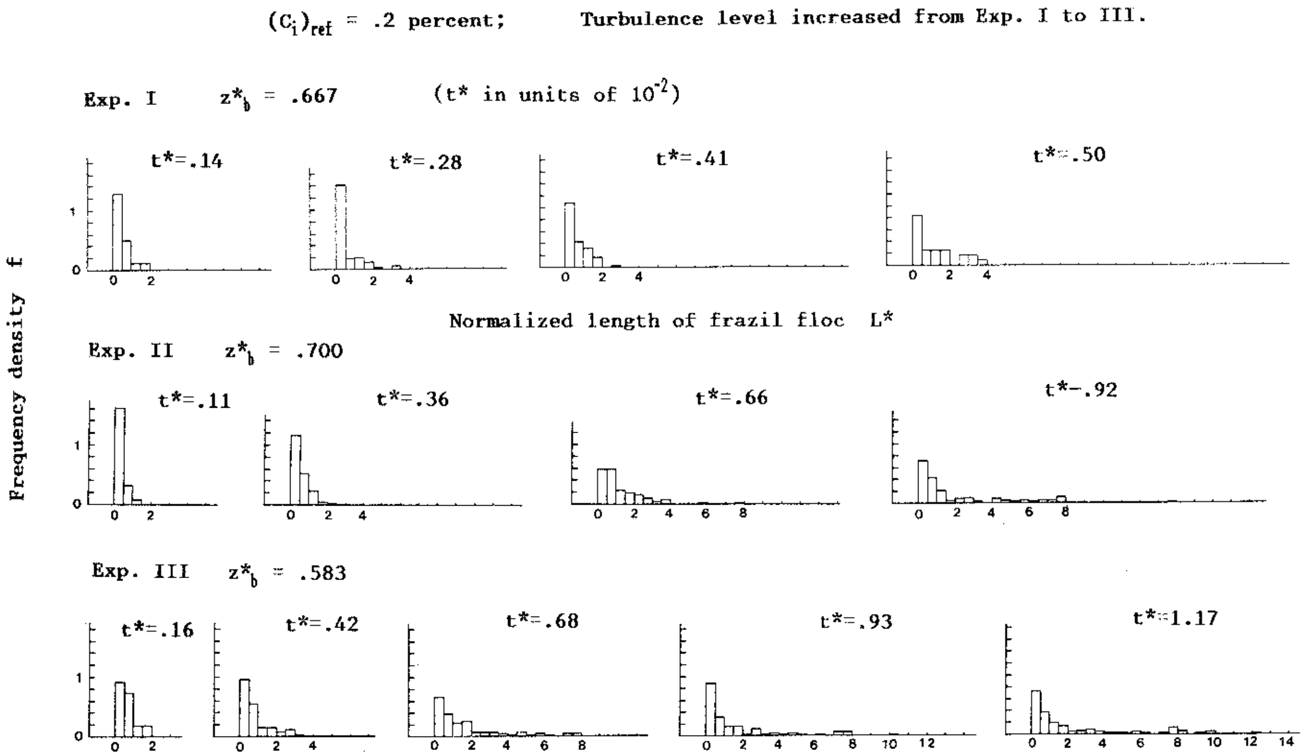

Fig. 3. Size Distribution of Frazil Flocs at the Middle Sensing Point at Different Times.

The above observations could be explained by the turbulent entrainment of frazil flocs by the flow. For a flow of given kinetic energy in the turbulence, it would be easier to pull the shorter flocs against buoyancy to the lower layer than to pull the longer flocs. This led to size distributions more skewed to the shorter end at lower depths. The maximum length of the flocs would also be less at lower depths.

It was shown earlier from Fig. 2 that near the surface, an increase in flow turbulence would lead to shorter flocs. At the lower measuring point, however, one sees a reverse of the above trend from Fig. 3. As the flow turbulence was increased from Exp. I to II to III, there was a progressive increase in the maximum floc length (For the same t*). The size distribution histograms were also became less skewed to the shorter end. Again this could be explained by turbulent entrainment of frazil flocs. When the turbulence level was low and the kinetic energy in the turbulence was limited, only short flocs could be entrained into the lower layers. However, as the turbulence level was increased, more and longer flocs could be entrained into the flow.

Figs 2 and 3 are for frazil flocs whose concentration was greater than 0.2 percent. It has been assumed that these flocs approximately represented all the frazil flocs in the flow. By changing the reference concentration from 0.2 percent to other values, frazil flocs of concentrations greater than the chosen reference values could be identified, and their size distributions investigated. Fig. 4 represents the results of such an analysis for Exp. III. At the top are size distribution histograms for $(C_i)_{ref}$=0.2 percent for five different times. These histograms are identical to those at the bottom of Fig. 2. The middle row of histograms are for $(C_i)_{ref}$=1.0

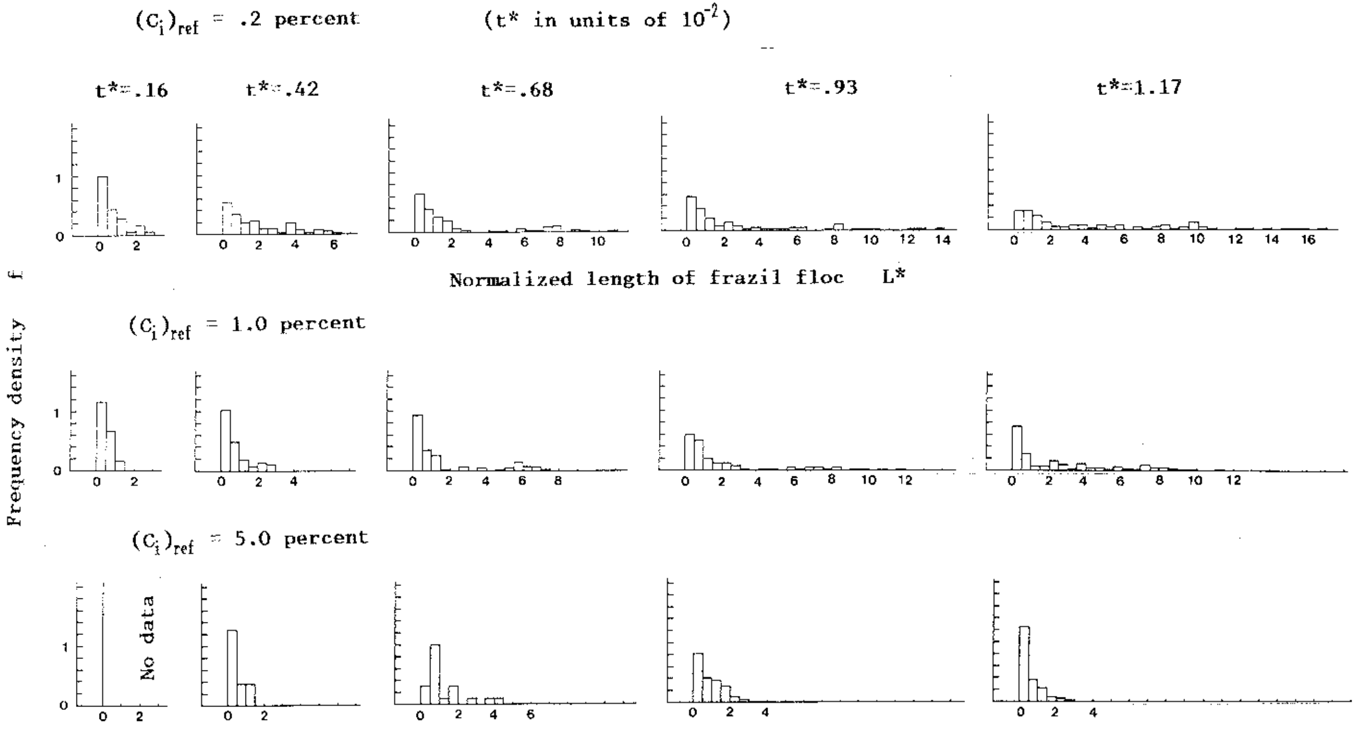

Fig. 4. Size Distribution of Frazil Flocs of Different Concentrations (Exp. III, near surface).

percent and the bottom row histograms are for $(C_i)_{ref}$=5.0 percent. The three rows of histograms are for the same times.

From comparing the histograms in Fig. 4, it become immediately evident that flocs of higher concentrations were shorter than those of lower concentrations at the given times. The distributions were also skewed more to the shorter end. For instance, at t*=1.17, while the longest flocs of $(C_i)_{ref}$=0.2 percent had a length of L*=17, for flocs of $(C_i)_{ref}$=1.0 and $(C_i)_{ref}$=5.0 percent, the longest floc length was reduced to 11.5 and 3 respectively. Also with $(C_i)_{ref}$ increasing from 0.2 to 1.0 to 5.0 percent, the histogram blocks of high f values are gradually shifted to lower L* values.

The floc size distribution characteristics shown above were also shown by measurements made at the second measuring point. Similar observations could also be said for Exps. I and II, both at the upper and the middle sensing points.

Shorter flocs for higher reference frazil concentrations were physically expected because a floc of higher concentration was always within a longer floc of lower concentration. The interesting observation was that, different from flocs of low reference concentration (0.2 percent), whose maximum length tended to increase with time, the maximum length of flocs of high reference concentrations (1.0 or 5.0 percent) seemed to increase with time first, then started to shrink, as shown in Fig. 4. Compaction of frazil flocs by turbulence offers an explanation to the above observation.

When a frazil floc was first formed, its frazil concentration was low. Three factors would contribute to increasing the concentration of frazil of this early agglomeration. The first was the incorporation of more suspended frazil crystals into the floc. The second was the growth of the ice crystals forming the floc, and the third was the compaction of the floc as it tumbled along in the turbulent flow. Under the combined action of these three factors, the concentration of frazil in the floc would increase to a value exceeding the reference concentration and be "seen" by the sensor probe. With the progress of time, more similar flocs would come to into existence and continue to grow. The compacting action, however, had two different effects on the frazil floc. First, it compressed the floc so that frazil concentration of the agglomeration would increase. Secondly, as the concentration was increased, the floc would also shrink if its loss in length was not sufficiently compensates by incorporation of more previously "unseen" frazil into the floc. At late stages of frazil evolution, the compressing effect would outweigh the growing effect, leading to an overall shrinkage of the frazil floc due to compaction. If this overall shrinkage due to compaction could not be compensated by the scavenging of frazil crystals from the flow by the floc and the growth of ice crystals forming the floc, there would be an net loss in the length of the frazil floc. It should be added that the compaction mentioned above also included compression of frazil flocs as they collided among themselves in the turbulent flow.

SUMMARY AND CONCLUSIONS

Frazil concentration in a turbulent flow was measured at three points in a laboratory experiment in which frazil formation and evolution was investigated from a Lagrangian frame of reference. The measured data showed a fast reduction of frazil presence with depth. The data obtained at the lower point were not analyzed because frazil presence at that depth was feeble and the sample size was too small to be statistically representative. From the measured data at the upper and middle sensing points, the size distribution of frazil flocs at different times and under various turbulence conditions was plotted in the form of frequency density histograms against the non-dimensional floc length. The histograms showed a decreasing distribution of flocs from short to long. As frazil evolved, longer flocs gradually developed. Near the surface, higher turbulence tended to break up the longer flocs into shorter ones, leading to a higher population for the shorter flocs. At the middle sensing point, however, higher turbulence was also able to bring long flocs to the lower layer, leading to a greater presence of longer flocs. As expected, the data showed that the higher was the reference concentration, the shorter would be the frazil flocs. The data also revealed that for the flocs of high reference concentrations, the floc length would increase with time first, then decrease with time as a consequence of compaction of the flocs by the turbulent flow. There seemed to be an upper limit to the length of the flocs. For the experiments, no floc was longer than 20 times the flow depth. A floc 6 to 8 time the flow depth would be considered "long". A high proportion of flocs had a length less than twice the flow depth.

No attempt is made at this point to propose a theoretical model for the size distribution of frazil flocs, nor are the data sufficient to justify advancing an empirical model. More work has to be done to further advance the knowledge on this regard.

There are other statistical parameters that are of interest to describe the evolution of frazil flocs. Among them are the probability of occurrence of frazil in the flow and the frequency of seeing frazil flocs in the flow. These two parameters are presently being investigated and findings will be reported in due time.

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REFERENCES:

Tsang, G. (1985), "An Instrument for Measuring Frazil Concentration", Journal of Cold Regions Sciences and Technology, 10, 235-242.

Tsang, G. (1989), "Laboratory of Frazil Evolution, Flocculation, and the Formation of Anchor Ice", Progress Report No. 1, National Hydrology Research Institute, Environment Canada, NHRI Cont. No.89070.

Tsang, G. (1990), "Laboratory of Frazil Evolution, Flocculation, and the Formation of Anchor Ice", Progress Report No. 2, National Hydrology Research Institute, Environment Canada, NHRI Cont. No.91057.