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Ice Slurry Cooling Research:

Microscale Study of Ice Particles Characteristics, Role of Freezing Point Depressant, and Influence on Slurry Fluidity*

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The influences of freezing-point-depressants on ice slurry characteristics in the form of ice slurry fluidity and on the microscale ice particle features are studied. The results identify microscale features of ice particles such as surface roughness that greatly influence slurry fluidity that are altered favorably by the use of a freezing point depressant. The engineering of a workable and efficient ice slurry cooling system depends very strongly on the characteristics of the individual ice particles in the slurry and, in turn, on the method of ice production. Findings from this study provide guidance on the fluidity and handleability of slurry produced by several methods currently under development and already many achieved.

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INTRODUCTION

Thermal energy storage has become recognized as an essential part of heating and cooling systems designed for reduced energy consumption and CO_2 emission. Both domestic and foreign users are adopting this technology for thermal systems with high heating and cooling loads. Thermal energy storage is especially attractive where cooling constitutes a significant part of the summer daytime electric peak demand. A portion of the cooling electric demand can be shifted to the nighttime period by making ice or chilled water at night and storing it for use the next day.

Using ice for district cooling has become of major interest in the form of captive tank storage and very recently as a pumpable slurry (in the form of an ice particle/water mixture). The pumpable slurry offers a great advantage in cooling capacity in both storage and pipe transmission over that of the chilled water that is used in conventional thermal energy storage systems (Kasza and Hayashi 1999; Liu et al. 1988; Larkin and Young 1989).

Both storage and pumped transmission of ice slurry to loads through piping have the advantage of allowing significant reductions in the size of piping, tanks, and chillers, as well as reduced system operating costs. However, in current cooling systems that use ice, the ice is held captive and melted in the storage tank to satisfy the cooling demand by using the stored cooling in the form of piped chilled water. The stored ice is not transferred out of the storage tank.

The ability to generate and store the ice slurry and retrieve/transfer it for use later, when cooling demand is high, is very important to the implementation of all the features of ice slurry cooling technology. Several studies that address the development of ice slurry cooling technology have been conducted on ice slurry generation, pipe transmission, and characterization. However, very little work has been performed on storage tank ice agglomeration and extraction or on how the microscale features of ice particles affect these important considerations.

This paper describes influences of freezing-point-depressants on ice slurry characteristics at both the macroscale level (ice slurry fluidity) and the microscale level (ice particle features) and relates the microscale features of individual ice particles to the general behavior of the slurry. This study also gives some preliminary guidance as to the inherent fluidity of slurries produced by different types of slurry machines.

INFLUENCE OF FREEZING POINT DEPRESSANT ON SLURRY CHARACTERISTICS

Many ice machines that are currently available or under development use a freezing-point depressant (an additive at concentrations of up to 15%) to minimize ice particle adherence to refrigeration cold surfaces. Various ice-making machines use different additives and can generate ice of different characteristics such as size, shape, and surface roughness. No known study has been performed to address the influence of ice particle microscale characteristics on slurry behavior or the role of additives in influencing slurry fluidity. We undertook the task of evaluating the influence of the additives on ice particle behavior during storage and extraction. Glycol is one of several additives that are or can be used with ice slurry machines. In this research, very weak aqueous solutions of ethylene glycol, up to 5 wt.%, were studied.

Ice Particles Used in Experiments

Ice particles from three sources were used in the experiments:

- Crushed Ice (Figure 1): chunk ice from harvesting ice machine, size range is 0.125 - 0.5 in. (3.2-12.7 mm).
- Shaved Ice (Figure 2): shaved in a snow cone machine from crushed ice, nominal size of 2 mm.

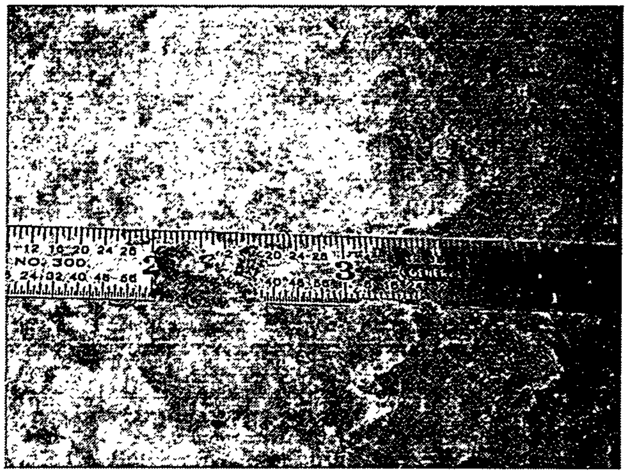

FIGURE 1. Crushed Ice

FIGURE 2. Shaved Ice

- Supercooling Formed Ice (Figure 3): Ice formed from various ethylene glycol aqueous solutions obtained by the supercooling method; size range is 0.5-2 mm, depending on degree of supercooling and concentration of ethylene glycol. In general the crushed and shaved ice particles are irregular and globular in shape and the supercooling particles are very elongated and dendritic.

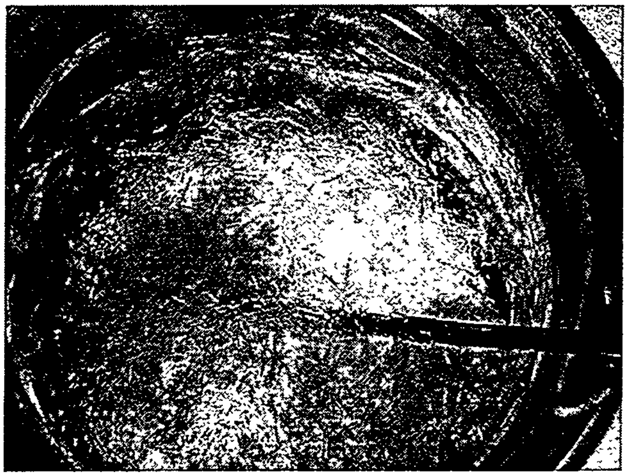

FIGURE 3. Supercooling Formed Ice

Slurry Mixing Experiment

The fluidity of a slurry for a given loading of ice particles in aqueous solution was formed to vary greatly depending on ice particle source and the presence of a freezing-point depressant such as ethylene glycol. The influences of these parameters on stored slurry fluidity were quantitatively explored through measuring the mixing intensity needed to homogenize a stored slurry ice bed.

Crushed ice and shaved ice were used in these experiments and both were tested for various ice loading percentages, slurry depth in tank, and glycol concentrations. The ice was formed without the presence of glycol and added to a given amount of tap water or to tap water having varying amounts of glycol to achieve various percentages of ice loadings and concentrations of glycol additives.

A schematic diagram of the beaker tank and magnetic mixing apparatus is shown in Figure 4, and Figure 5 is a photograph of the apparatus. The desired slurry ice loading for a given test was obtained by adding a known weight of ice particles to a known weight of precooled tap water. When ethylene glycol was added, its concentration was calculated against the weight of the water in the slurry. The resulting slurry was loaded into a 2000 mL glass beaker, measuring ϕ 5.0 x 7.5 in. tall which is stirred by a magnetic stirrer with a 2-in.-long stirring bar, and at rotation speeds from 0–1100 rpm.

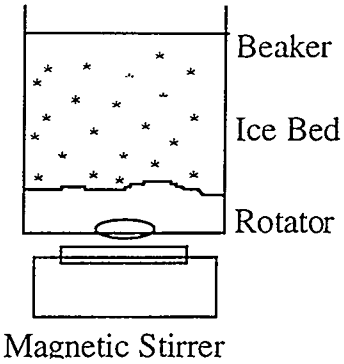

FIGURE 4. Schematic Diagram of Mixing Experiment Apparatus

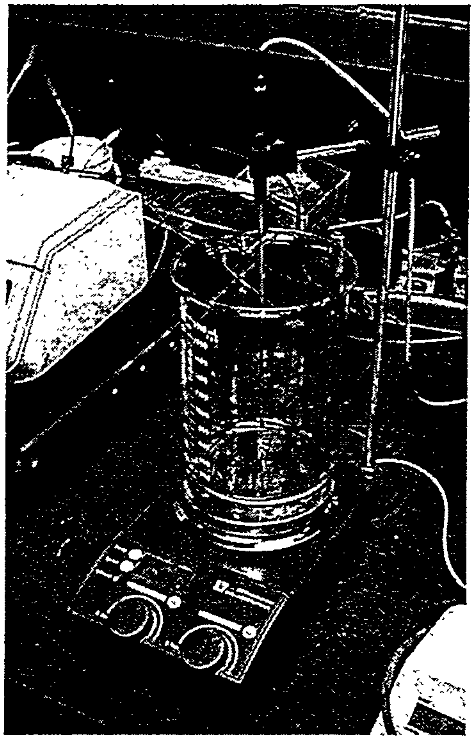

FIGURE 5.. Mixing Experiment Apparatus

For each test, the rotational speed at which the slurry ice bed was completely mixed was measured. In some cases, the ice bed could not be completely mixed. A layer of stationary ice would remain at the top of the beaker. Figures 6-9 show the mixing results for both crushed and shaved types of ice particles for tap water and various glycol concentrations. In each figure, the vertical axis represents the mixer rotating speed (rpm) needed for complete mixing, while the horizontal axis represents stored slurry ice loading in wt.%. The lower the rotation speed needed for complete mixing, the better the slurry fluidity.

Figure 6 shows the result for the crushed ice and tap water slurry mixture in various ice loading and various total weight, i.e., various slurry height in the beaker. Slurry height (h) increased by 1.25 in./400 g slurry. It is apparent that rotating speed needed for mixing slurry increases with increase in ice slurry amount and with increased ice loading. Also, the solid squares in Figure 6 represent a total slurry amount of 1200 g (the same as for the open square case) where ice particles are smoothed by thermal melting. The removal of roughness was evaluated by the procedures later. The required rotating speed was significantly reduced for the ice particles smoothed by some melting. This suggests that particle surface roughness strongly influences slurry fluidity. Hence, in a slurry system a small amount of thermal premelt of slurry, which reduces particle roughness, before storage can be helpful in improving fluidity as will be shown later. Particle smoothing can also be obtained chemically by using a freezing point depressant.

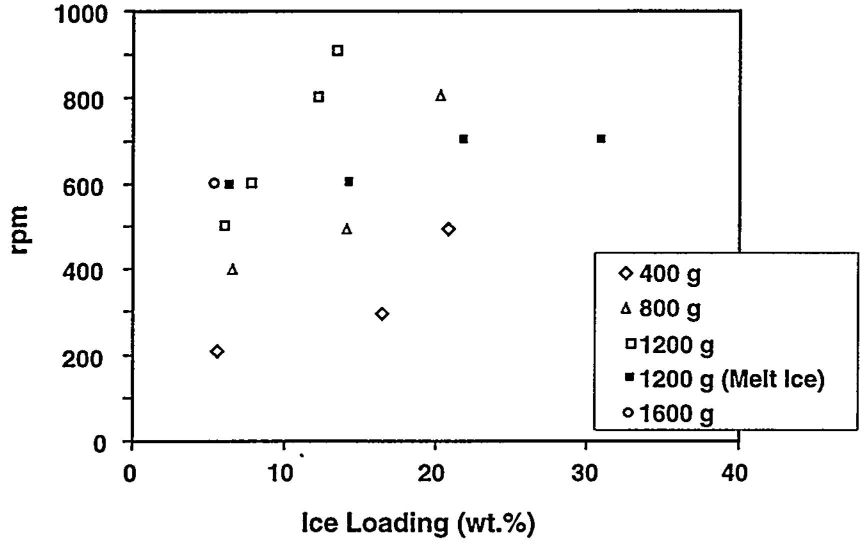

FIGURE 6. Rotation Speed Needed for Mixing Ice Slurry in Various Amounts, and Ice Loading (Tap Water, Crushed Ice)

Figure 7 shows the influence of ethylene glycol on the mixing fluidity of the crushed ice slurry. Adding glycol significantly improved fluidity. The higher the concentration of ethylene glycol, the greater the effect. Furthermore, a very small amount of glycol (0.5 wt.%) yielded a significant improvement in fluidity as can be seen by comparing the 0 wt.% and 0.5 wt.% cases. The increase in fluidity is present at 3 wt.% glycol but the improvement is diminishing; the reason will be discussed in detail later.

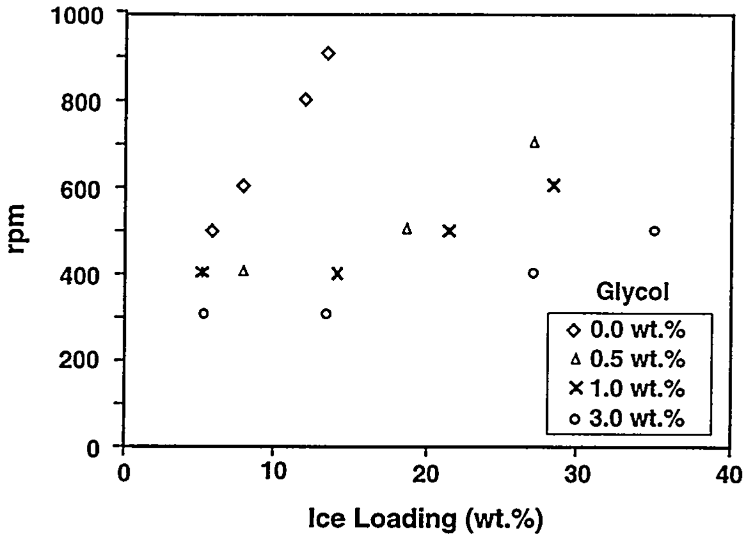

FIGURE 7. Rotation Speed Needed for Mixing Ice Slurry in Various Amounts, and Ice Loading (Ethylene Glycol Solution, Crushed Ice)

Figure 8 shows results similar to those of Figure 6 (ice particles plus tap water, no glycol), with the only difference being the use of shaved ice, which had much smaller ice particles than crushed ice. Compared with Figure 6 for crushed ice slurry, a higher rotation speed was needed for mixing the shaved ice than the crushed ice. In fact, no ice loading above 10 wt.% could be mixed with the apparatus. Hence, shaved ice slurry has lower fluidity than crushed ice slurry even though the particles were much smaller.

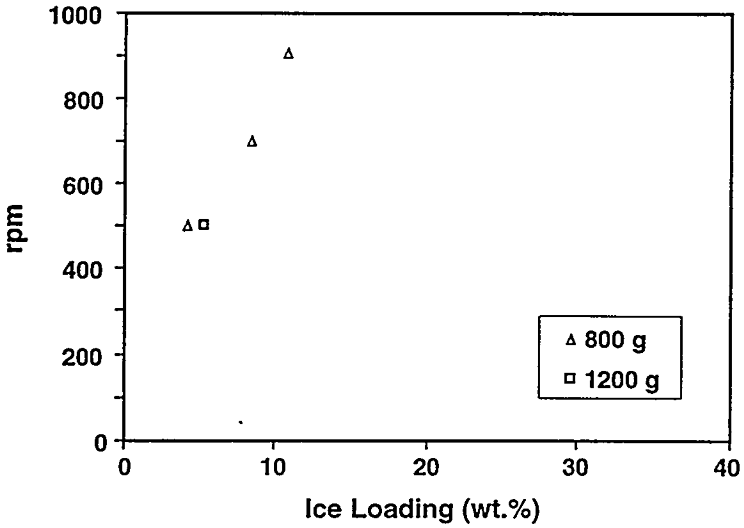

FIGURE 8. Rotation Speed Needed for Mixing Ice Slurry in Various Amounts, and Ice Loading (Tap Water, Shaved Ice)

Figure 9 shows the results for the shaved ice slurry with added ethylene glycol. The effect of glycol in improving fluidity and mixability of the ice bed was smaller than that for the crushed ice.

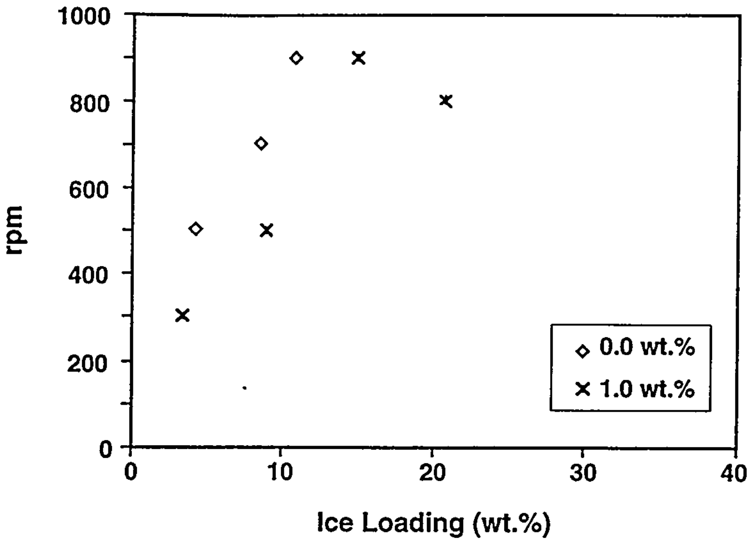

FIGURE 9. Rotation Speed Needed for Mixing Ice Slurry
in Various Amounts, and Ice Loading (Ethylene Glycol Solution, Shaved Ice)

The difference between shaved ice and crushed ice is size, shape, and roughness of particles; shaved ice proved more difficult to mix than crushed ice.

In summary, ice slurry fluidity was evaluated by measuring the mixing intensity (i.e., mixer rpm) needed for complete mixing of an initially stored ice particle and water/solution. The following results were obtained:

- Mixing intensity required to uniformly mix the stored slurry increases with increase of the total ice slurry amount and ice loading %.
- For crushed ice, required mixing intensity was significantly reduced by initially using either particle thermal melt or addition of glycol, a freezing-point depressant, both of which smooth the ice particles. This suggests that particle surface roughness and probably shape plays a significant role in dictating slurry fluidity.
- Higher mixing intensity was needed for shaved ice than for crushed ice stored under identical total slurry amounts and ice particle % loading. This illustrates that the method for making ice particles can be a significant factor in determining slurry fluidity or ease of mixing. The effect of glycol was also smaller for shaved ice than that for crushed ice slurry.

In the next section where the microscale features of the ice particles are evaluated, the reason for this behavior will be evident.

Microscale Study of Ice Particles Characteristics and Role of Freezing Point Depressant

Microscope Investigation. During the mixing experiments, we discovered that freezing-point depressant additives can significantly improve slurry fluidity. Ice particle size, shape, and roughness is deemed as having a strong influence on slurry behavior. To understand the role of particle characteristics in slurry behavior, the microscale roughness of ice particle surfaces was characterized in both the absence and presence of various concentrations of ethylene glycol to assess the effect of glycol on ice particle roughness. Three different sources of ice particles were characterized relative to particle roughness before and after addition of small amounts of glycol to the slurries.

Figure 10 shows the experimental apparatus. Figure 11 shows the test cold cell where slurry is observed with a microscope to study the ice particles. Magnification in the range of 6x to 50x was used. The cold cell is comprised of four parallel plates of glass of roughness 4 in. x 4 in. In the center chamber for holding slurry the two plates of glass are 0.25 in. apart. On both sides of the center chamber is dead air space formed by an air gap created by a glass plate separated by 1/8 in. gap which reduces heat gain to the slurry. The ice particles in the cold cell were backlighted to gain the brightness needed for the video camera and also to better delineate surface roughness. The images are split in two by a prism. One output was monitored by a TV monitor through a video camera and the other was photographed by a 35-mm camera.

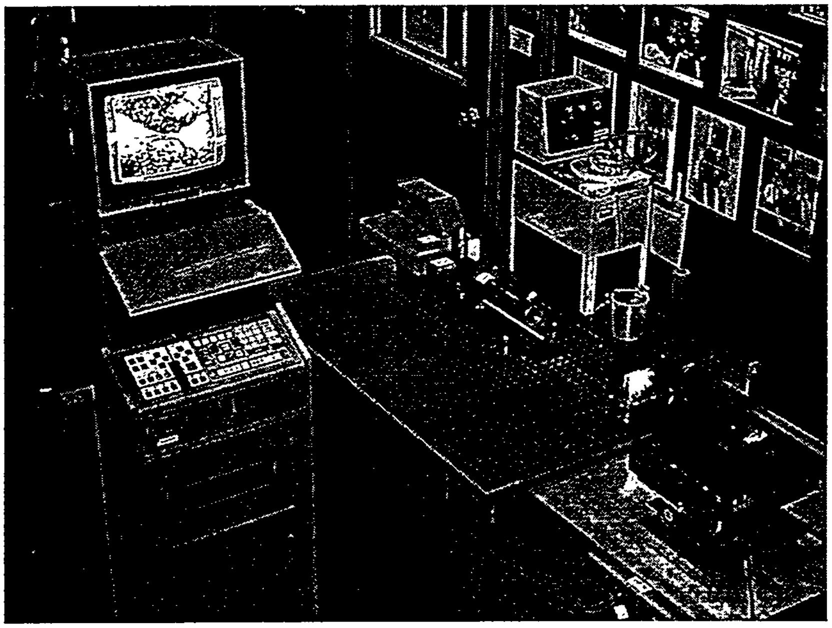

FIGURE 10. Slurry Microscale Study Apparatus

Observed Ice Particles. Figures 12-16 are magnified photos of the three different types of ice used in these studies with and without glycol. Figure 12 shows crushed ice suspended in tap water; small ice globules are sticking or frozen on a larger particle, making the large particle surface very rough. Figure 13 shows crushed ice after being loaded into the cold cell containing an aqueous glycol solution. The particles are very smooth compared to those in Figure 12; the small globules have been melted by the glycol, slightly reducing the freezing point of the slurry mixture. Like the glycol treated particles, particles in Figure 12 were also found to be smoothed if allowed to melt for a period of time due to a small addition of heat to the mixture in the cold cell.

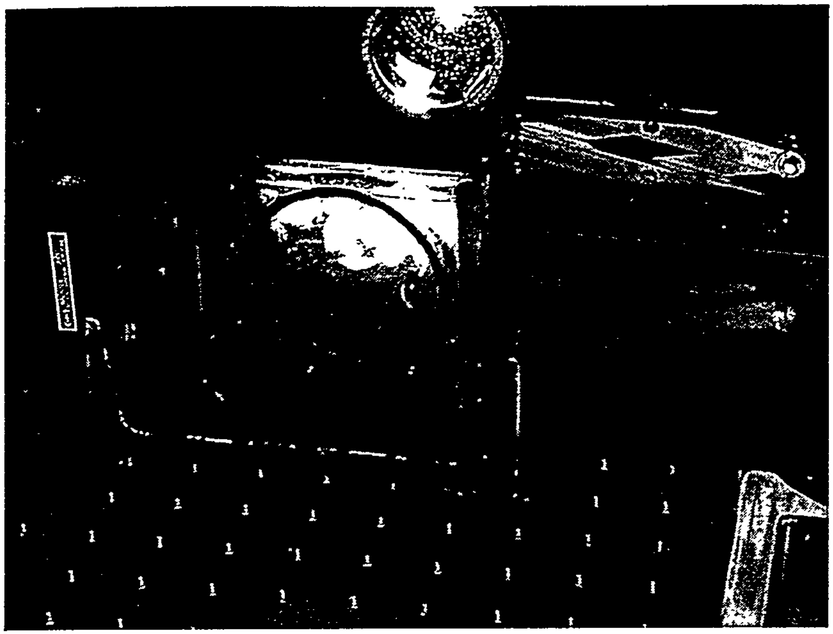

FIGURE 11. Test Cold Cell and Lighting

Ice particles generated by supercooling ice (Figure 14), comprise very large dendrites with a very high aspect ratio and also extensive roughness. The dendritic particles were found in the cold cell tests to remain elongated (but shorter) and dendritic even if allowed to melt or if glycol is added. No corresponding picture is shown for smoothing of dendritic ice particles formed by supercooling, but the general effect of glycol was to shorten the particles but not effectively smooth them. The persistent rough and elongated nature of dendritic ice even with melting glycol causes these particles to experience a high level of enlargement and clustering which greatly reduces their fluidity.

Ice particles produced by shaving ice from larger chunks are shown in Figures 15 and 16, suspended in tap water and an aqueous glycol solution, respectively. The difference between the chemically untreated crushed-ice particles of Figure 12 and those for shaved ice in Fig. 15 is that the shaved ice is composed of small particles of very similar sizes, while the crushed ice contains larger particles in a much greater size range. The individual shaved ice particles display very little roughness. However, the shaved ice consists of small globular particles frozen together, yielding larger rough-particle clusters. This is because the shaving process causes heating, melting, and refreezing, allowing the individual particles to be freeze-joined into complex clusters. Shaved-ice particle clusters adversely affect slurry fluidity because the clusters will be entangled more easily than the crushed-ice particles. Moreover, the shaved-ice particles, even after being suspended in glycol solution, become smaller but remain rough in overall shape (Figure 16). The use of glycol additive failed to melt the freeze connection between interconnected and clustered and particles. This is the reason why the shaved ice slurry showed lower fluidity than the crushed ice which did not improve with addition of glycol as described in the mixing experiment section. If the crushed ice particles had been pressed and stored for some period, causing large particle freeze-joining and clustering, they would also not have been smoothed as efficiently by glycol.

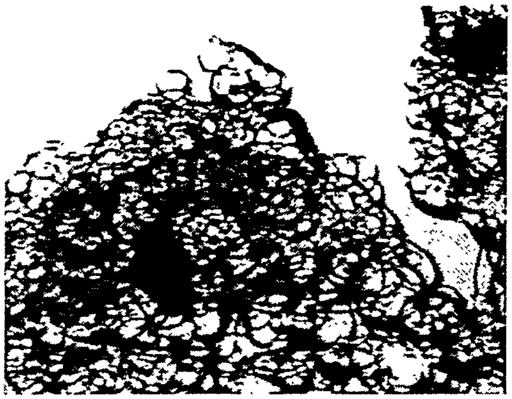

FIGURE 12. Crushed Ice in Tap Water

FIGURE 13. Crushed Ice Smoothed by Glycol Solution

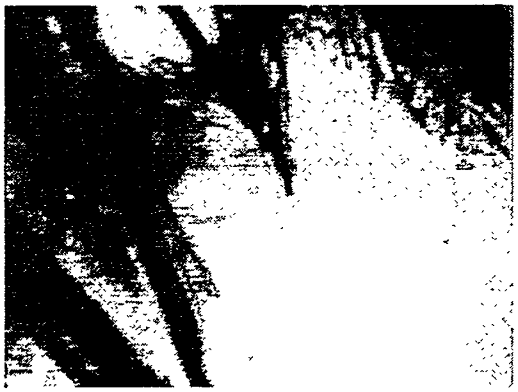

FIGURE 14. Supercooling Ice in Tap Water

FIGURE 15. Shaved Ice in Tap Water

FIGURE 16. Shaved Ice in Glycol Solution

Quantitative Evaluation of Particle Roughness. The preceding discussion on particle-roughness improvement with glycol additive was qualitative. Efforts were made as follows to more quantitatively evaluate surface roughness reduction and the role of glycol. The surface roughness of ice particles was quantitatively evaluated from magnified ice-particle pictures, i.e., a two-dimensional evaluation based on particle silhouettes. A perimeter, L, and area, A, of individual ice particles in pictures typical of those shown earlier were measured using NIH Image software. A parameter L*, the perimeter of a circle having the same area as the ice particle silhouette, was calculated. A parameter L', the actual ice particle perimeter L normalized by the equivalent circular area perimeter L*, was defined:

$$L' = L/L^* . \qquad (1)$$

The larger the value of L', the rougher the ice-particle shape/surface. This criterion was then used to quantify the change in surface roughness characteristics for crushed ice with various amounts of glycol.

Figure 17 shows the variation of normalized roughness L' with glycol concentration. The vertical axis represents the normalized roughness, L', while the horizontal axis represents the ethylene glycol concentration. For each glycol concentration, 50 to 70 photographed particles were evaluated and the averaged value of normalized roughness L' was plotted in Figure 17.

As shown in Figure 17, the roughness of the crushed ice particles was reduced by almost 10% by adding ethylene glycol. Although the change is not large, it has a significant implication in that it represents the removal of the very small surface roughness that has a large impact on overall fluidity. These small-scale protuberances on larger particles prevent particles from readily slipping by each other, causing particles to entangle and cluster. As shown in Figure 17, L' is reduced with addition of glycol up to 1 wt.%. However, little change in L' is seen above 1 wt.% glycol. This change in surface roughness, as inferred by a reduction in L', explains why a very small amount of glycol, 0.5 wt.%, is so effective in improving slurry fluidity in the mixing tests of previous section.

From the results of the slurry mixing experiments and the microscope cold-cell investigations, the melting and smoothing of the protuberances of ice particles is identified as one of the mechanisms which greatly improves the ice slurry fluidity resulting from the use of a freezing point depressant thermal melting. Thus it is shown that microscale characteristics of ice particles have a great influence on macroscale ice slurry fluidity. The considerations essential to the engineering of a workable and efficient ice slurry cooling system depend very strongly on the roughness characteristics of the individual ice particles in the slurry and, in turn, on the method of ice production.

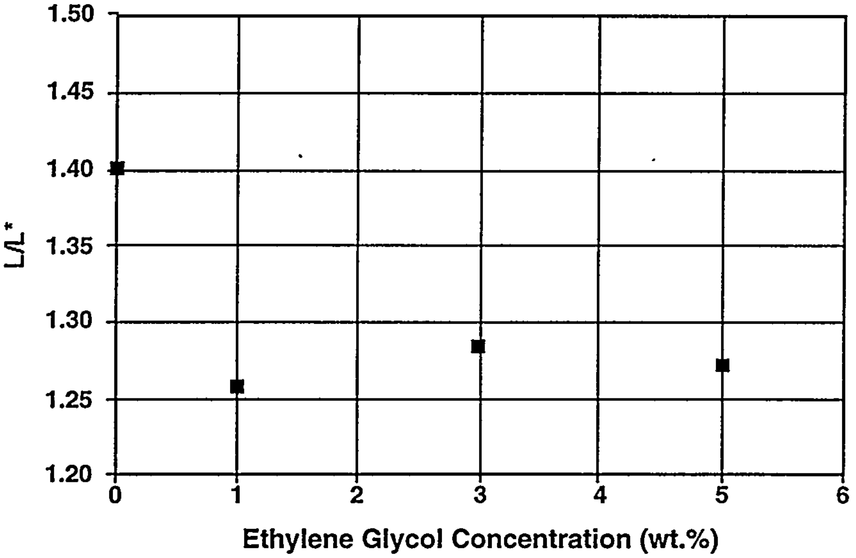

FIGURE 17. Crushed Ice Particle Roughness (L/L*) vs. Ethylene Glycol Concentration

CONCLUSIONS

Influences of freezing-point-depressant on ice slurry characteristics in both aspect of macroscale (ice slurry fluidity) and microscale (ice particle features) were described. The results identify microscale features of ice particles such as surface roughness that greatly influence slurry fluidity that are altered favorably by freezing-point-depressant. Findings from this study provide guidance on the fluidity and handleability of slurry produced by several methods currently under development. The findings from these small-scale investigations of slurry fluidity have been used to conduct large-scale ice slurry storage and mixing experiments at Argonne. The results from this effort will be presented in a followon paper.

ACKNOWLEDGMENTS

These studies were conducted at Argonne in a collaborative program between NKK Corporation, Japan, and Argonne National Laboratory (ANL), based on the recognition that the remaining technical issues hindering the use of ice slurry cooling are focused on storage tank agglomeration and extraction. The work reported here was fully supported by NKK Corporation, Tokyo, Japan, under a Work For Others agreement with Argonne National Laboratory.

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