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ICE SLURRY COOLING RESEARCH: STORAGE TANK ICE AGGLOMERATION AND EXTRACTION*

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ABSTRACT

A new facility has been built to conduct research and development on important issues related to implementing ice slurry cooling technology. Ongoing studies are generating important information on the factors that influence ice particle agglomeration in ice slurry storage tanks. The studies are also addressing the development of methods to minimize and monitor agglomeration and improve the efficiency and controllability of tank extraction of slurry for distribution to cooling loads. These engineering issues impede the utilization of the ice slurry cooling concept that has been under development by various groups.

INTRODUCTION

Over the last 10 years, interest in thermal energy storage has grown significantly. Today, both domestic and foreign interests are considering adopting this technology for thermal systems that involve large cooling and heating loads. Thermal-energy storage technology is especially attractive where a portion of the summer daytime electric peak demand, of which cooling constitutes a significant part, can be shifted to evening periods by making ice during evening hours and storing it for use the next day. The storage of ice in tanks for electrical load shifting is a very attractive feature of ice cooling. Depending on the density of the ice packing, an ice storage tank can be as small as 1/10 the size of a tank used to store an equivalent cooling capacity of chilled water.

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In current ice storage/load shifting systems, the ice produced and stored during the night is melted in the storage tank to satisfy the cooling demand by using the stored cooling as chilled water that is piped to loads. The ice is not transported out of the storage tank. Recently, the transportation or pumping of ice itself as a slurry has received considerable attention (1-3). Because of the high cooling content of ice slurries, which is due to the phase change (melting) of the ice particles under a cooling load, the cooling capacity of a slurry pumped to a load can be up to five times greater than that of chilled water delivered at the same mass-flow rate (4-6). This high energy content allows significant reduction of the size of slurry transmission piping and storage tanks at a central plant and at the end user from that required for a conventional chilled-water cooling systems (4-6).

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 slurry cooling technology. Several studies that address the development of ice slurry cooling technology have been conducted on ice slurry generation, ice slurry pipe transmission, and ice slurry characterization. A good survey of pertinent studies is presented in Ref. (7). However, very little work has been performed on storage tank ice agglomeration or extraction.

Production of ice slurries

Several methods have been developed or are under development for the generation of ice particles that are suitable for ice slurries. In general ice generation is less efficient than that of chilled water generation, because of the lower temperature required to generate the ice. Therefore, ice maker efficiency is a very important issue. Prevention of ice maker equipment freezeup is also important, to ensure a reliable source of ice particles. Typical techniques, which use pure water, are of the Ice Builder Harvester , Supercooling (8), Vacuum (9-11), and Direct Contact type (12). In addition, other methods of ice particle generation are based on binary solutions of water and chemicals such as freezing-point depressants (11, 13). Various units are commercially available.

Pipe transmission of ice slurries

Various studies of ice slurry pipe transmission have shown that ice slurry can be used effectively as a energy transport medium to replace chilled water. If of the proper size and correct loading, ice particles in water can be pumped with no greater pumping power penalty than that for conventional chilled water (1,14,15). Moreover, under conditions of appropriate particle size and ice loading fraction and with the addition of an appropriate flow-friction-reducing chemical additive, slurries can even be pumped with considerably less power than that needed for chilled water (14).

Characterization of Ice Slurries

To reliably operate an ice slurry cooling system, it is very important that we know the ice loading fraction in the ice slurry storage tanks and in the slurry transmission piping, as well as the bulk inventory of the stored ice slurry. Several approaches to measurement, based on the difference between the conductivity or specific volume of water and ice, have been investigated and developed, as described in Refs. (16-18). A method for measuring the presence and progression of ice particle agglomeration in storage tanks is needed.

PURPOSE OF STUDY

The storage of ice slurry in tanks is complicated because under certain not-well-understood conditions, the ice particles progressively grow together, or agglomerate, over time, making pumping of the slurry out of the tank very difficult, if not impossible. Furthermore, because it is desirable to store the slurry at the highest possible packing density to most effectively utilize tank size, the slurry, even if it does not agglomerate in the tank, must be carefully diluted to a packing density that is compatible with pumping it through a pipe delivery network. It is known that pump efficiency and pipe pressure drop can be adversely influenced if the slurry loading is too high (14). No reliable procedure has been developed to extract slurry from a tank or control the loading of slurry into the distribution piping.

The purpose of the program described in this paper is to study the factors that influence slurry tank agglomeration, develop methods to mitigate this problem, and explore ways to more effectively extract the slurry and control its loading density for delivery to cooling loads. The information being developed will facilitate the use of ice slurry cooling.

AGGLOMERATION STUDIES

When ice slurry at high particle loading is stored in a tank, individual particles have a tendency to agglomerate, i.e., freeze together. Over time, the individual particles can form large porous masses of agglomerated particles that cannot be pumped from the tank to the cooling loads. Even with vigorous mixing, the agglomerated particles can be very difficult to break down to a pumpable size. Furthermore, the mixing constitutes a parasitic energy loss to be minimized or avoided. For very large tanks, mixing becomes impractical. The tendency for agglomeration and the rate at which it progresses is a function of many poorly understood parameters, such as particle size and shape, tank loading density, ice particle bed height, water chemistry, tank agitation intensity, and storage time. The influence of these parameters on slurry storage tank agglomeration is being studied in this program. Various approaches to the reduction of agglomeration, such as addition of small amounts of chemicals to the water and several methods of stirring, are being explored. Instrumentation that will allow us to measure the degree of tank agglomeration as a function of time is also under development. This instrumentation is very important to the successful operation of storage tanks. The goal is to establish the conditions under which the slurry can be stored for at least 12-24 h without detrimental agglomeration.

TANK EXTRACTION/CONTROLLED PIPE LOADING STUDIES

To maximize the cooling capacity associated with a storage tank of a given size, the slurry should be stored in tanks at higher loading than can be effectively pumped and piped to cooling loads. The slurry particle loading in the distribution piping must be maintained at <30% in an efficient and controlled manner to keep transmission losses low (14). Also, the efficiency of centrifugal pumps begins to deteriorate if the ice loading fraction is too large. Various methods of controlled extraction of slurry at the desired distribution loading are being explored. The ice particle bed that resides in the storage tank in the absence of stirring (the preferred mode of operation to keep parasitic energy expenditure to a minimum) may be at 50% or higher loading. Methods of blending this dense slurry with a diluting water stream for distribution are being explored. Various storage tank access ports and pipe/pump configurations are also being explored.

Improved design and operation guidelines for storing and extracting slurry will be available when these two studies are completed; the result will be a more efficient and reliable slurry system design.

FACILITY DESCRIPTION/MODES OF OPERATION

This section describes the features of a new facility being used to perform the ice slurry studies. Figure 1 shows a simplified schematic representation of the experimental apparatus that is being used to study storage tank ice agglomeration and extraction.

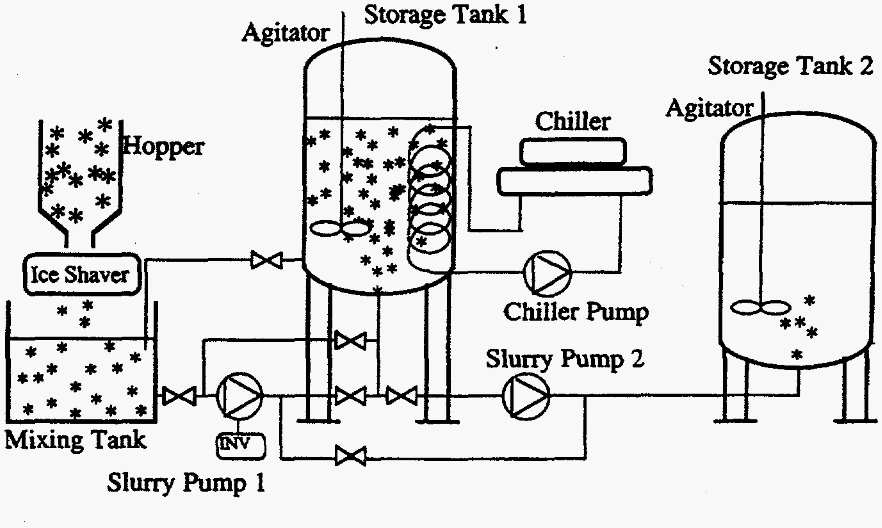

Fig. 1. Experimental apparatus used to study storage tank ice agglomeration and extraction

The facility equipment includes two almost identical 800-gal stainless steel slurry storage tanks fitted with large stirrers and in-tank cooling coils connected to a 17.6-ton chiller that adjusts tank temperature before slurry is released from the ice shavers. Because ice particle size is an important test parameter that influences agglomeration, tank extraction, and slurry pumpability, the ice particle generator consists of ice shavers that allow generation of ice particles of differing size. The ice particles generated by the ice shavers are mixed with pre-cooled 0°C water in a small mixing tank. The ice/water slurry is then pumped to the 800-gal storage tank (Storage Tank 1) by a centrifugal slurry pump. Batch-charging of the storage tank with specific quantities of ice and water is used to obtain the desired tank loading for a given test. The slurry can be transferred from the storage tank by a variable-speed pump capable of pumping slurry at up to 40-50% loading. A 100-gal slurry characterization/weighting tank (not shown) is used to accurately determine the loading fraction for the tank extraction studies. A magnetic flow meter is also used to determine flow rate. The storage tanks have several ports that are used for instrumentation and for exploring the influence of the slurry/extraction point and piping configuration on extraction efficiency.

A typical test involves three steps:

- Ice particle generation/tank charging. During this step, ice slurry with the desired particle size is generated and loaded into the storage tank to the desired loading.
- Ice slurry storage. The ice slurry is stored in the storage tank and the rate at which agglomeration progresses is measured over time.
- Ice slurry extraction. The ice slurry is extracted from the storage tank and the effectiveness of the extraction method and the pumpability of the ice slurry are investigated/evaluated.

Major Subsystems of the Facility

Storage Tank 1 (Fig. 2)

The agglomeration and extraction/controlled loading studies are mainly performed in Storage Tank 1. Ice slurry is loaded and stored in this tank for 12-24 h and the agglomeration rate is measured as a function of time. After the storage period, the ice slurry stored in this tank is extracted by either centrifugal Slurry Pump 1 or progressing-cavity Slurry Pump 2, which is capable of pumping very high particle loadings. Specifications for Storage Tank 1 are

Stainless steel
1.5 m in diam x 1.7 m tall, volume = 800 gal
Ports: one 18 in., two 6 in., one 1.5 in., two 1 in., and one 0.5 in.
Stirrer (mixer): air driven, 1.3 kW (at 2.8 bar air, 3000 rpm)
In-tank copper coil to cool water before ice loading

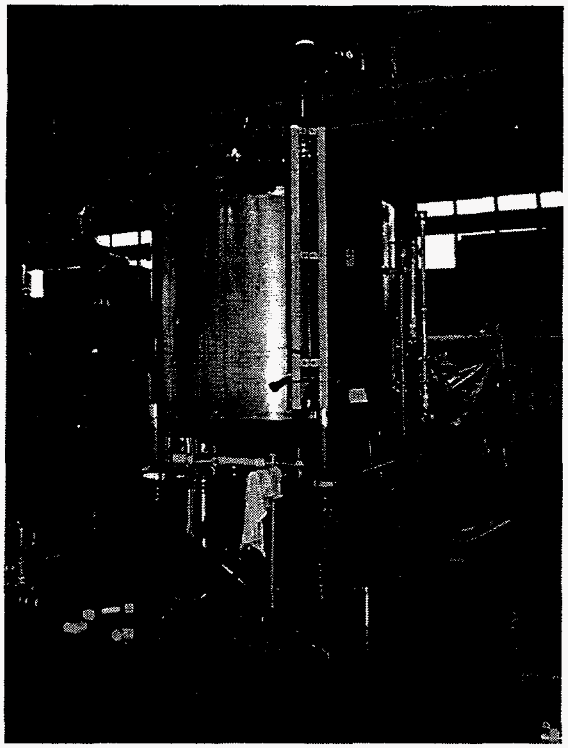

Fig. 2. Storage Tank 1

Storage Tank 2 (not shown)

Storage Tank 2 is almost identical to Storage Tank 1; it is connected to Storage Tank 1 by a 15-m slurry transmission pipe. The ice slurry extracted from Storage Tank 1 is pumped into and stored in Storage Tank 2. Specifications for Tank 2 are the same as those for Tank 1 except for the ports, which in Tank 2 are one 18 in., one 1.5 in., one 1 in., and two 0.5 in.

Ice Shavers (Fig. 3)

The ice shavers generate ice particles of various sizes from ice cube feed stock. Three ice shavers are used. Information on generated particle size and production rate is present in the Preliminary Data section. Each ice shaver is driven by a 3/4 hp electrical motor and is adjustable to produce ice particles of various sizes.

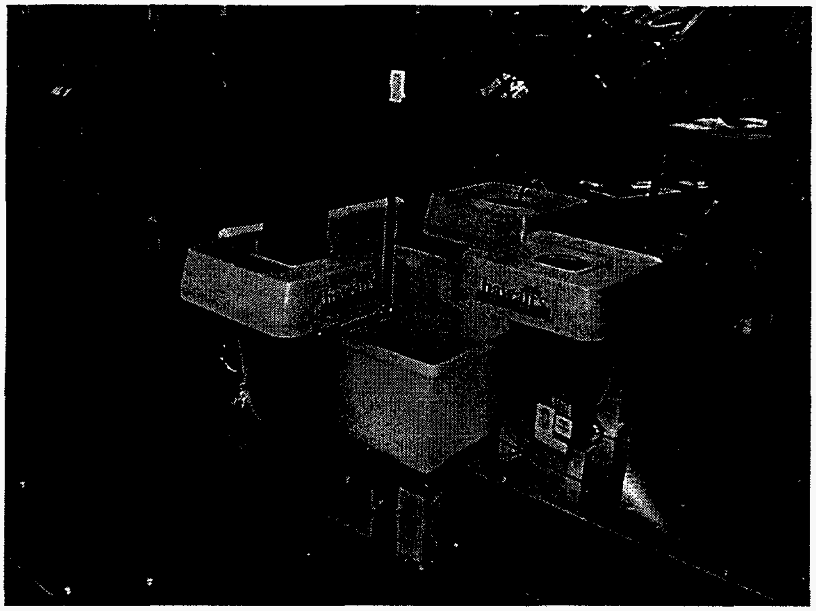

Fig. 3. Ice shavers and mixing tank

Mixing Tank (Fig. 3)

The plastic mixing tank receives ice particles that drop down from the three ice shavers. The particles are mixed with precooled 0°C water from Storage Tank 1. The mixture of ice and water (ice slurry) is pumped from the mixing tank to Storage Tank 1. Water at 0°C that is devoid of ice is returned to the mixing tank to transfer more ice to Storage Tank 1. Specifications for the mixing tank are

20 in. long x 30 in. wide x 24 in. tall, volume = 94 gal
Ports: four 2 in., two 1.5 in.

Chiller (Fig. 4)

A 17.6-ton (61.9-kW) chiller is connected to the in-tank cooling coil of Storage Tank 1. The chiller precools the water inside Storage Tank 1 to nearly 0°C to prepare it to receive ice particles from the mixing tank (slurry generation system).

Slurry Pump 1 (not shown)

Slurry Pump 1 is a 3-hp centrifugal pump with an open impeller that is used to pump the ice slurry. This pump is speed-controlled by an inverter and can be used in two processes. For ice slurry tank charging, this pump transfers ice slurry from the mixing tank to Storage Tank 1. This pump can also be used for extracting ice slurry from Storage Tank 1.

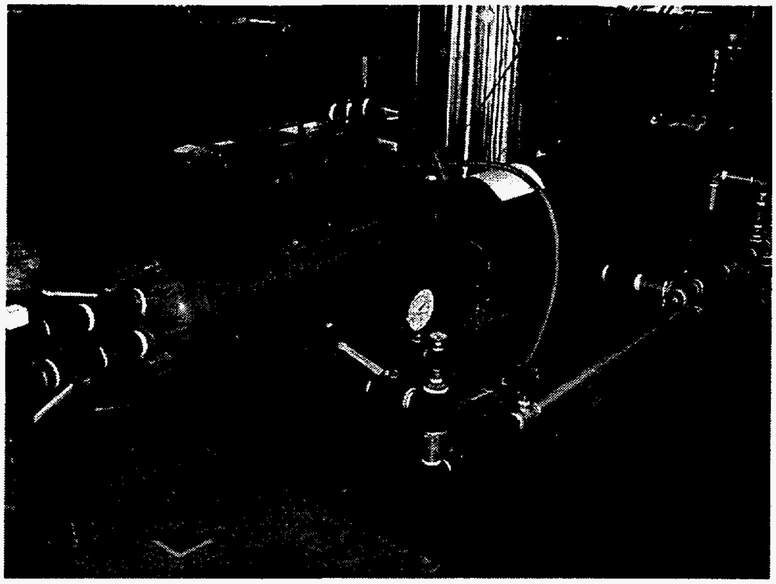

Fig. 4. Chiller

Slurry Pump 2 (Fig. 5)

Slurry Pump 2 is a 7.5-hp, speed-controlled, progressing cavity displacement type pump. It can pump ice particles of up to 0.8 in. at high loading. Either Slurry Pump 1 or Slurry Pump 2 can be used to extract ice slurry or to transfer slurry to Storage Tank 2 from Storage Tank 1.

Fig. 5. Slurry Pump 2

Water Pump (not shown)

This 3/4-hp centrifugal pump with an open impeller is used to transfer the chilled water from Storage Tank 1 to the mixing tank during the ice slurry charging process.

Slurry Characterization Tank (not shown)

This is a 0.756-m-diam x 0.953-m-tall, 113-gal stainless steel tank that is used to accurately determine the loading fraction and flow rate of the extracted ice slurry as small quantities of the ice slurry flow are momentarily diverted into the tank and weighed.

EXPERIMENTAL PARAMETERS

The degree of agglomeration of ice particles of various size and loading, stored in the storage tank, is monitored as a function of time. The monitoring is performed to investigate the effect of several parameters on ice particle agglomeration and to develop approaches to prevent/reduce agglomeration. The parameters and their range of variation are presented below:

Ice Particle Size

Based on preliminary evaluation particle size is anticipated to have a significant influence on the agglomeration. The ice particle size in these experiments is controlled by setting the ice shavers. The size range being explored, from a fraction of a mm to 10 mm, spans the ice particle sizes produced by ice makers that are commercially available or under development.

Tank Ice Loading Density (Ice Particle Bed Height) at 10-50% of Tank Volume

Ice agglomeration is promoted by increasing the contact pressure between ice particles. (See Experimental Techniques and Preliminary Data section on Agglomeration Measurement.) Contact pressure is directly related to ice bed height in an unstirred tank where ice particle buoyancy packs the bed.

Water Chemistry: Tap Water and Several Additives

The reference against which the effectiveness of various additives for reducing agglomeration will be compared is tap water. Certain additives can prevent or reduce agglomeration by forming a liquid layer around the contacting ice particles. This layer reduces freezing tendencies. Several freezing-point depressants and surfactants are being evaluated. Additional criteria that will be used in selecting additives are cost effectiveness and absence of environmental concerns.

Tank Agitation

Agitation or mixing of the slurry in the tank is expected to reduce agglomeration tendency. Both mechanical mixing and jet-induced mixing are being explored. The need for agitation should preferably be eliminated or kept to a minimum to promote high system efficiency. We hope that water chemistry tests will eliminate or significantly reduce the need for tank agitation.

Storage Time

Agglomeration increases with slurry storage time. Experimental storage time will range from a few hours to 24 h. Agglomeration is measured by the method described in the next section.

In the tank slurry extraction experiments, the slurry that is stored in the storage tank for varying periods of time is pumped into a second tank or returned to the original tank through piping. Several extracting points and pipe configurations of Storage Tank 1 are being tested to optimize extraction efficiency. The slurry will be extracted at various flow rates. The influence of slurry characteristics on pipe and fitting pressure drop is also being explored. Small samples of the pumped slurry are momentarily diverted into a slurry characterization tank where mass-flow rate and particle loading are evaluated to characterize the controllability of extraction and the consistency of the slurry loading.

EXPERIMENTAL TECHNIQUES AND PRELIMINARY DATA

Generation of Ice Particles

Experiments have been conducted on the ice shavers to determine shaving productivity and particle size controllability. Data for the fine and coarse settings are presented. Ice particles of nominal sizes 0.5 and 2 mm are obtained at the fine and coarse settings, respectively, of the shavers. The shape and temperature of the ice feedstock for the shavers were also varied as follows:

Ice Shape
- Ice 1: Cube (1.25 x 1.25 x 1.25 in.)
- Ice 2: Cylindrical (1 x 1.25 in.)
- Ice 3: Crushed (size ranged from 0.25 to 1 in.)

Ice Temperature
- Melting Point: 0°C (32°F)
- Sub-Cooled: approximately -11°C (12°F)

The shaving capacity (productivity) of a single shaver is shown in Fig. 6, which shows that capacity of the shavers is greater with melting point ice than with subcooled ice for the fine or coarse setting. For the subcooled ice, the capacity increases as the size of the feedstock ice increases. On the other hand, no similar relationship can be seen between the capacity and the size of feedstock ice for the 0°C (32°F) ice. When three ice shavers and No. 2 ice at 32°F are used with a coarse setting, the 800-gal storage tank can be charged to a 50% ice loading in <1 h.

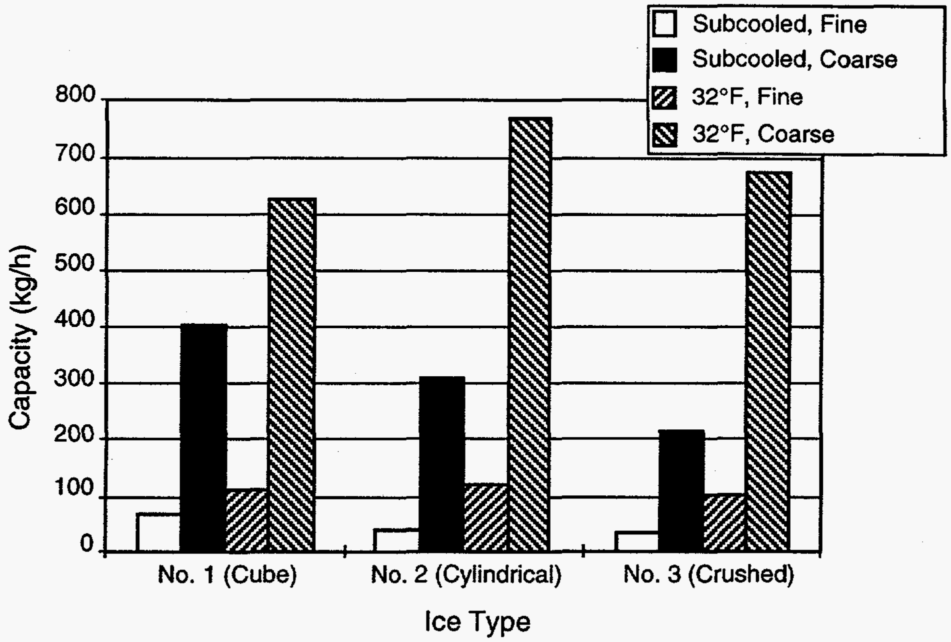

Fig. 6. Results of ice shaving test

Agglomeration Measurement

Several methods are being developed to measure ice particle agglomeration. One of the methods is based on using the large difference in the electric conductivity (resistivity) between ice and liquid water. This new technique will be very important to ice slurry system operators in monitoring the status of stored slurry so agglomeration doesn't proceed to the point that slurry extraction becomes impossible and the slurry cannot be distributed to cooling loads. The newly developed sensor, shown in Fig. 7, is used to measure the resistivity of a local small volume of the slurry (a volume that contains a representative number of ice particles and water). Figure 8 shows the measurement sensor immersed in a tank of ice slurry.

Figure 9 shows the sensor output for an ice slurry composed of pure water and ice particles and depicts behavior when agglomeration occurs. Figure 10 shows the sensor output for an ice slurry in which a small amount of antifreeze (ethylene glycol) has been added to the water and depicts behavior that exhibits reduced agglomeration that is a result of adding the antifreeze. The vertical axis in each figure denotes the normalized resistivity of the ice slurry. The normalization accounts for water behavior with no ice particles (measured by the reference electrodes located within a screen ice barrier; see Fig. 8) as well as the condition immediately after tank charging with slurry. Time zero corresponds to completion of tank charging.

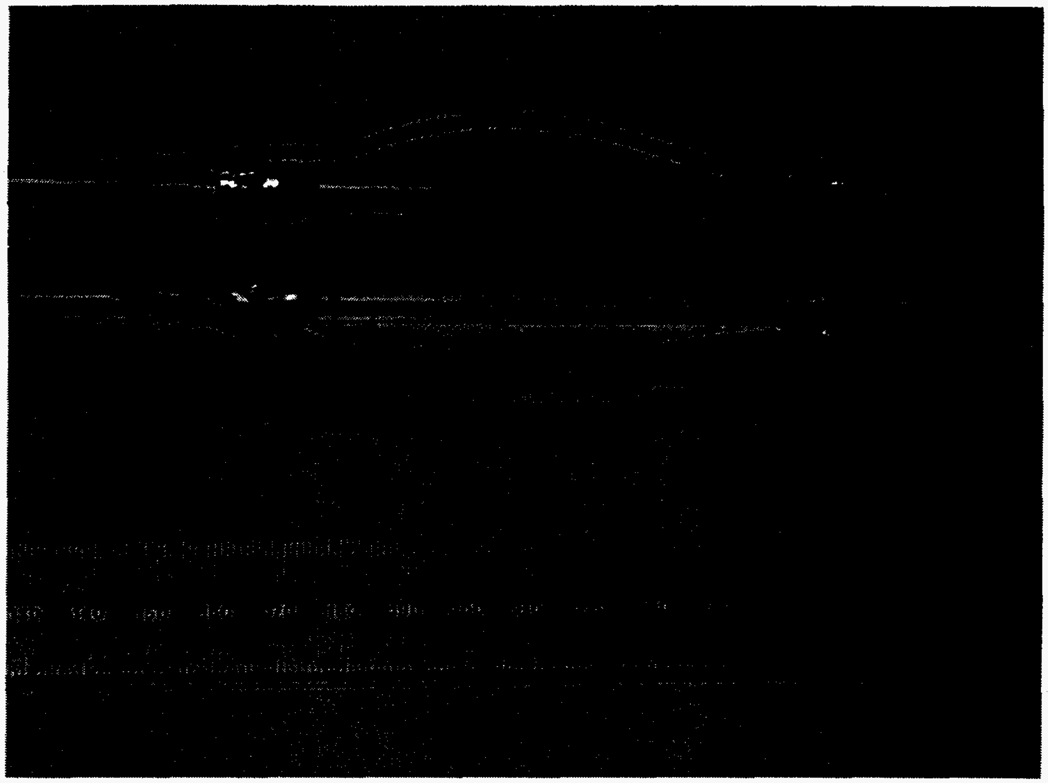

Fig. 7. Ice agglomeration sensor

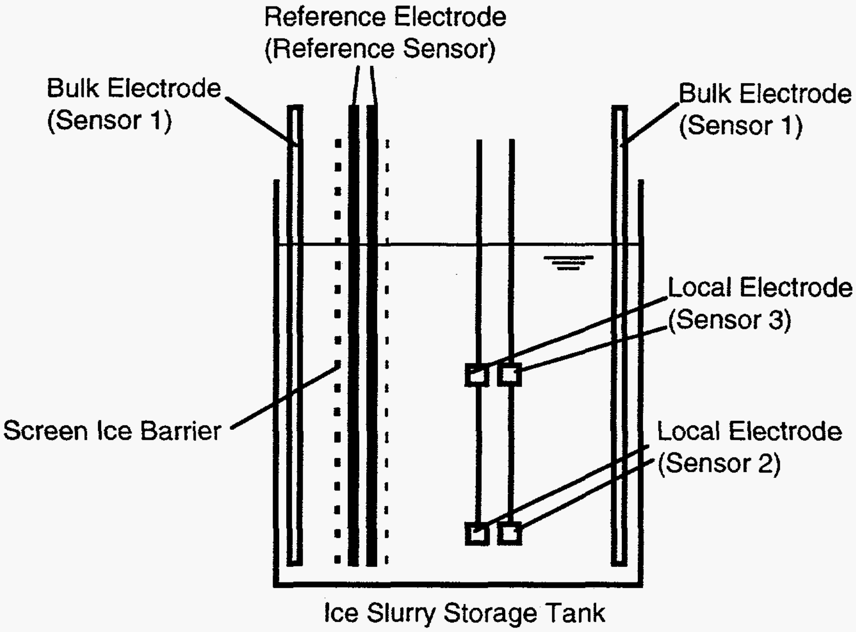

Fig. 8. Apparatus used to measure ice agglomeration

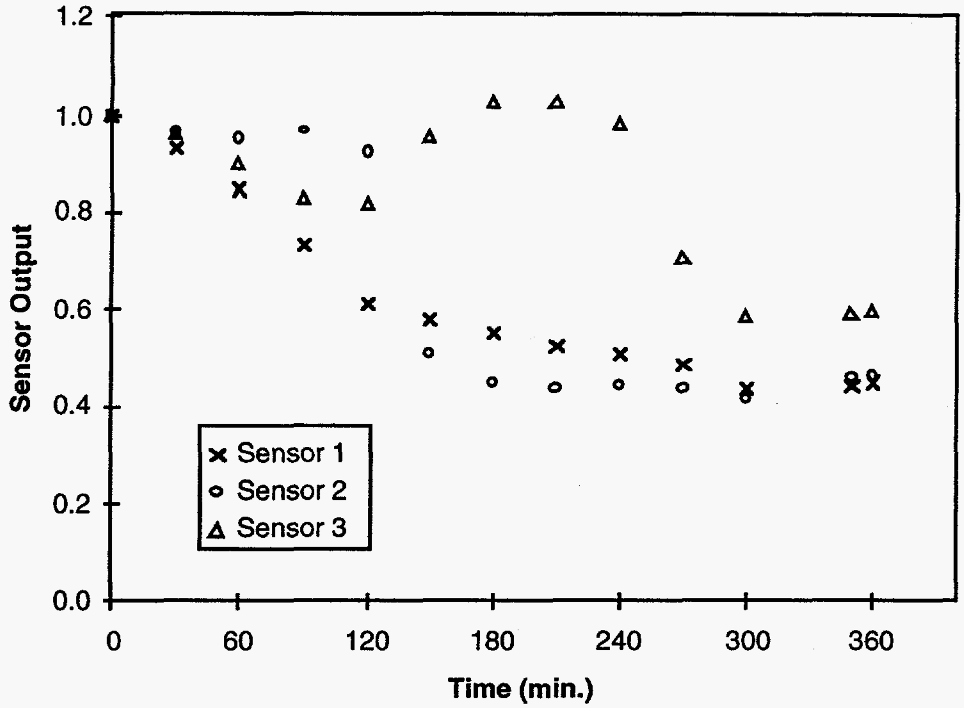

Fig. 9. Sensor outputs for pure-water ice slurry when agglomeration occurs

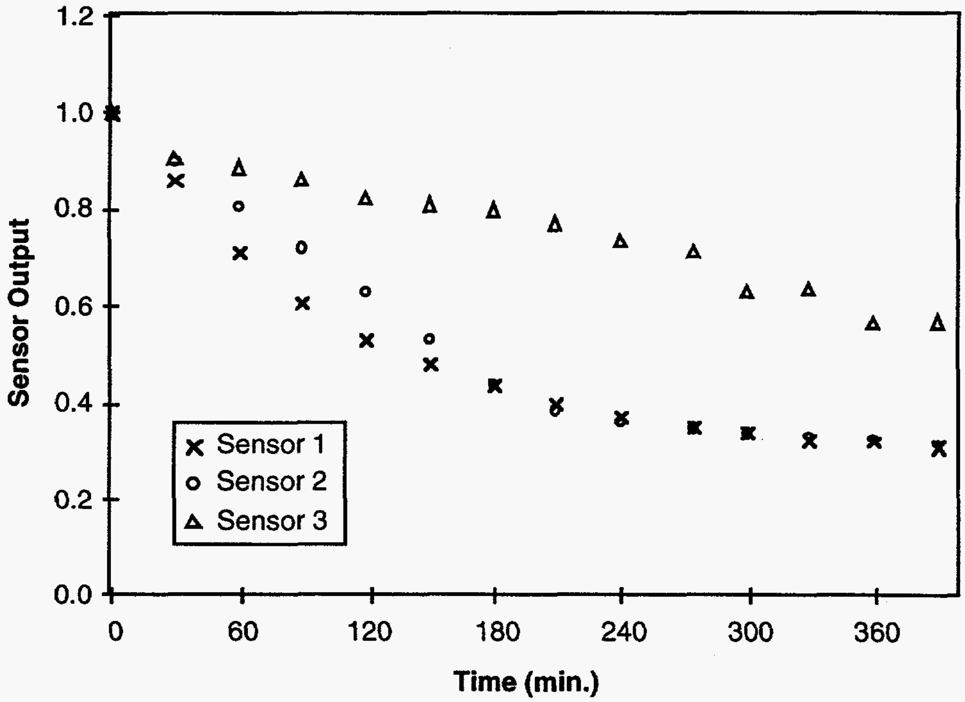

Fig. 10. Sensor outputs for ice slurry with antifreeze, showing reduced agglomeration

Sensors 1 measure the resistivity of the bulk ice slurry in the tank. Sensors 2 and 3 measure the local resistivity at two elevations in the slurry. In Figs. 9 and 10, the output of Sensors 1 decreases with time because the mean ice loading of the test tank is decreasing because melting is occurring as a result of heat gain from the surroundings. In Fig. 9, pure water slurry, Sensors 2 and 3 (the local measurements) show significant peaks at 80 and 200 min, respectively. These peaks do not occur in Fig. 10, which depicts slurries to which antifreeze has been added. The peaks with pure water are caused by an increase in local electrical resistivity. The increase in local resistivity with time is a result of ice particles becoming more tightly packed. Ice bed packing pressure from gravity loading causes the irregular particle/particle contact protuberances to progressively melt and refreeze, allowing the particles to physically join and become more tightly packed in the ice bed. Hence, the local resistivity measurements of Sensors 2 and 3 show increased output. After peaking, the output of Sensors 2 and 3 decrease suddenly because the local sensors move out of the bulk ice bed because of overall bed melting. The signals from Sensors 2 and 3 differ because they are at different elevations in the tank ice bed. Hence, the ice particles at the different elevations experience differing packing pressure and melt/refreeze rates. In addition, the sensors are at different distances from the top and bottom surfaces of the ice bed where melting takes place and the bulk volume of ice decreases with time.

Additional experiments to quantify the rate of agglomeration with various additives, ice particle sizes, and sensor configurations are underway.

CONCLUSIONS

A new facility has been built at Argonne National Laboratory to conduct research and development on vital issues related to implementing ice slurry cooling technology. The studies underway are generating important information on the factors that influence ice particle agglomeration in ice slurry storage tanks. The studies are also addressing the development of methods to minimize and monitor agglomeration and to improve the efficiency and controllability of extracting slurry from tanks for distribution to cooling loads. The information being developed will furnish improved design and operation guidelines for ice slurry cooling systems and facilitate the general implementation of the technology.

ACKNOWLEDGMENTS

These studies are being conducted in a collaborative program between NKK Corporation, Japan, and Argonne National Laboratory (ANL). Starting in 1982, ANL, under U.S. Department of Energy funding, pioneered the development and fostered the concept of advanced energy transmission fluids (that employ phase-change particle slurries and flow-friction-reducing additives) as enhanced energy transport media for large conventional heating and cooling systems that currently use water as the energy transport media. The current ice slurry cooling studies, which started in 1997, are an outgrowth of that work. NKK has been developing various aspects of the ice slurry cooling technology since 1992 and has conducted studies on developing an ice slurry generator and instruments for measuring tank and pipe ice loading, and investigated ice slurry pipe flow pressure drop. The present program is based on the recognition by ANL and

NKK that the remaining technical issues that hinder the use of ice slurry cooling center around storage tank agglomeration and extraction.

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