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ICE SLURRY APPLICATIONS

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Abstract

The role of secondary refrigerants is expected to grow as the focus on the reduction of greenhouse gas emissions increases. The effectiveness of secondary refrigerants can be improved when phase changing media are introduced in place of single phase media. Operating at temperatures below the freezing point of water, ice slurry facilitates several efficiency improvements such as reductions in pumping energy consumption as well as lowering the required temperature difference in heat exchangers due to the beneficial thermo-physical properties of ice slurry. Research has shown that ice slurry can be engineered to have ideal ice particle characteristics so that it can be easily stored in tanks without agglomeration and then be extractable for pumping at very high ice fraction without plugging. In addition ice slurry can be used in many direct contact food and medical protective cooling applications. This paper provides an overview of the latest developments in ice slurry technology.

Keywords

Ice slurry; cold storage; food industry; surgery; protective hypothermia

1. INTRODUCTION

The use of ice for prolonging the storage life of food dates back many millennia. Up until the middle of the 19th century all ice used for cooling was obtained from natural sources such as winter snow/ice or imported arctic ice. Sometimes the natural snow was mixed with salt in order to reach lower temperatures. The first ice cream was produced using this “technology” some two thousand years ago in ancient Rome.

With the introduction of mechanical refrigeration, ice could be produced in different forms such as block, cube, tube or flake ice. Most of these forms of ice require a certain degree of manual operation for transportation from one place to another, and have rather sharp edges that may damage a product’s surface when used for direct contact chilling. Furthermore,

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they are usually quite coarse and have poor heat transfer performance when releasing their latent heat of fusion.

Ice slurry refers to a homogenous mixture of small ice particles and carrier liquid. The liquid can be either pure freshwater or a binary solution consisting of water and a freezing point depressant. Sodium chloride, ethanol, ethylene glycol and propylene glycol are four most commonly used freezing point depressants in industry. Over the last two decades interest in using phase-change ice slurry coolants has grown significantly (Kauffeld, *et al.*, 2005).

Ice slurry has a high energy storage density because of the latent heat of fusion of its ice crystals. It also has a fast cooling rate due to the large heat transfer surface area created by its numerous particles. The slurry maintains a constant low temperature level during the cooling process, and provides a higher heat transfer coefficient than water or other single phase liquids. These features of ice slurry make it beneficial in many applications. For example, the ice slurry based thermal storage system produces and stores cold in the form of a dense ice slurry during nighttime hours when electricity is cheap, and the cold energy can then be quickly released by melting the ice slurry for air-conditioning of buildings during daytime hours when electricity might be several times more expensive.

In some applications ice slurry can be made during periods of no demand and be stored for later use. Both the high energy storage density and the pumpable delivery of ice slurry to the cooling loads make it possible to achieve significant reductions in the size of tanks, pumps, piping, and chillers. The reliable pumping of high ice fraction slurry also referred to as high “ice concentration” out of a tank and through a distribution system without plugging up has only become feasible recently. Studies have shown that ice slurry must be engineered to have the correct ice particle characteristics (size, globular shape and smoothness) in order to achieve its full potential as a coolant (Kasza and Hayashi, 2001a; Kauffeld et al., 2005). The use of ice slurry has the potential to greatly improve the effectiveness of District Energy Systems and to protectively cool patients experiencing medical emergencies such as cardiac arrest or during planned surgeries. Ice slurry can also be used as a cold storage medium in various vessels without built-in refrigeration systems such as ice slurry cooled trolleys, trucks or fishing boats.

The “Handbook on Ice Slurries – Fundamentals and Engineering” published by the International Institute of Refrigeration provides a comprehensive review of various applications for ice slurry prior to 2005 (Kauffeld, *et al.*, 2005). It includes many examples of indirect contact cooling applications from comfort cooling of buildings and gold mines to process cooling of breweries, dairies and produce. However, it has only limited coverage of direct contact cooling applications. Fish processing and supermarket display cases are the only two examples briefly described in the book. Over the last five years there have been a large number of installations completed in over 40 countries for direct contact cooling of various food products. This paper discusses the latest developments in ice slurry as a secondary refrigerant and direct contact cooling technology used in bakery, produce packing, fishery, as well as its new emerging application for protectively cooling organs during medical emergencies and surgery. Market demands and challenges are also discussed for each industry, as well as a detailed description of the state-of-the-art solutions being used.

2. CHARACTERISTICS OF ICE PARTICLES IN ICE SLURRY

Among others, Kasza and Hayashi have shown that ice slurry must be engineered at the micro-scale to have the correct ice particle characteristics (2001a). In general ice particles produced and suspended in pure water produce ice slurry with poor fluidity as commonly experienced by anyone trying to enjoy an ice slush drink by sucking through a straw; the ice remains in the cup. A microscope system has been used to study ice particle shapes and surface roughness for ice slurry with good and bad handling characteristics. Figure 1(a) shows an example of bad ice slurry made in a blender with pure water. As shown the ice slurry when poured through a funnel plugs up the funnel and only water is delivered to the beaker. The two microscope image inserts in Figure 1(a) show two types of ice particles which make bad ice slurry: dendritic particles which are very rough and elongated and form large entangled clusters causing plugging and globular particles with rough surfaces which entangle to a lesser degree but still are far from optimum. As depicted in Figure 1(b) using methods which involve adding a freezing point depressant chemical to the carrier liquid (in this case salt) to smooth ice particle surface roughness and employing additional thermal melting smoothing during production results in dramatic improvements in ice slurry fluidity; the ice slurry readily flows through the funnel into the beaker without plugging. Removing the surface roughness of the individual ice particles at the micro-scale level allows the highly loaded ice particles to slip past one another without tangling or agglomerating eliminating funnel plugging. The very best ice slurry is made from ice particles that start globular in shape; ice slurry made with dendritic ice particles can be improved using chemical and thermal smoothing but not as dramatically as for globular particles. The large aspect ratio of dendritic ice particles, even though the particles are small, promotes particle clustering and entanglement.

The two methods for ice particle smoothing (chemical and thermal) can be used separately or in combination during the ice slurry production process depending on the method of ice production and on the quality of ice slurry required. Chemical smoothing is induced by the use of freezing point depressants such as ethylene glycol, propylene glycol, ethanol or various salts such as sodium chloride. Thermal smoothing results from adding measured amounts of warmer coolant to the ice slurry mixture during production. Careful use of these methods of particle smoothing dramatically improves the engineering handling characteristic of ice slurry. The required use of a freezing point depressant such as glycol represents an element of cost and complexity. Other chemicals and methods of ice particle engineering are being explored. The use of ice slurry has the potential to greatly improve the effectiveness of distributed-load cooling systems and is also being developed for medical applications.

The strong influence that chemical smoothing of individual ice particle surface roughness has on the engineering mixing characteristics of ice slurry is demonstrated through the use of a simple bench-scale apparatus. The apparatus consists of a 4 litre beaker sitting on a variable speed magnetic drive mixer platform. Testing involved filling the beaker each time with 3 litres of ice slurry having varying ice loadings from 5 to 35 % by weight made using an aqueous based carrier liquid containing low percentages of ethylene glycol (0 to 3 %) and gradually increasing the mixer rpm from zero until the point at which the stored ice slurry is fully involved in mixing bottom to top.

As shown in Figure 2 (Kasza and Hayashi, 1999), the impact of chemical smoothing on the mixing characteristics of ice slurry is dramatic. Without glycol, ice slurry with ice loading greater than 13 % could not be mixed effectively bottom to top. With increasing amounts of glycol, the slurry is capable of being mixed at much higher ice loadings. For example, with 3 % glycol a 35 % loaded ice slurry is capable of being mixed at a mixer rpm of 500 rpm. The freezing point depressant reduces particle entanglement by smoothing the surface roughness on individual ice particles and allows particles at the higher loadings to slip by each other which greatly reduce mixing energy dissipation. In addition the smoothing also allows the ice slurry to be pumped out of the container much easier and flow through delivery conduits at much higher loadings without plugging.

3. ICE SLURRY GENERATION

The most important issue relating to the implementation of ice slurry cooling technology still relates to what is the best method for making the ice and converting it into ice slurry for a particular application. There are several ice making methods which manifest themselves as commercial ice making devices; the device selected for a given ice slurry cooling application must be chosen carefully because of the differences in the type of ice particles they produce. Some types of devices available produce dendritic ice as indicated below:

- Super cooling of water and sudden bulk nucleation of ice crystals* (Bédécarrats *et al.*, 2010)
- Freezing point depressants in aqueous binary solution and scraped or moveable cold surfaces to facilitate removal of ice particles (Stamatiou *et al.*, 2005)
- Cyclic freezing and thawing of an evaporator surface (Kauffeld *et al.*, 2005)
- Vacuum triple point of water* (Kim *et al.*, 2001) or evaporation of the freezing point depressing alcohol (Asaoka et al.,2009)
- Ice Harvester with ice chunk crusher/shaver/cutter
- Direct freeze process (spraying of water into cold gas or other fluid medium) (Wijeysundera *et al.*, 2004)

* Produces dendritic ice particles which even after chemical and thermal smoothing have large length to diameter aspect ratios and are more prone to entanglement.

Most ice slurry installations use ice generators of the scraped surface type. In many of the installations, initial investment costs are higher due to this kind of ice generator. Often operating costs are similar to operating costs with other refrigeration systems. But typically energy consumption of distribution pumps are reduced by approximately 40 % as compared to non-phase changing media. Sometimes cost savings can also be obtained in energy costs (ice slurry storage in Japan, where building electricity rates can be 3 to 5 times lower during night than during day time) higher value of the chilled product can be obtained (e.g. fish preserved in ice slurry), or productivity improvement through reduction in labour, ice consumption and/or waste.

Recently, further improvements in making and delivering ice slurry have resulted from the need to develop slurries for medical protective cooling applications. For this application, described in Section 6, ice slurry is made using ice particle smoothing yielding ice slurry which can be pumped at over 50 % ice loadings through tubes smaller than 1mm in diameter.

Some of the newer ice slurry applications will be described in the following paragraphs.

4. ICE SLURRY APPLICATIONS INCORPORATING HEAT EXCHANGERS

The ability to store ice slurry without agglomeration or particle entanglement during storage and then pump it out of the tank as a homogenous mixture is very important to the implementation of ice slurry cooling technology and achieving its full potential. In some applications, it is advantageous to make ice slurry during off-peak demand periods (night time) and store it for later use (afternoon periods). For the majority of past ice thermal storage systems, the ice was not pumped out of the tank only chilled water was piped to points of load. The ice slurry or ice chunks were melted in the storage tank. Both central storage and pumped transmission of ice slurry to loads has the advantage of allowing significant reductions in the size of piping, pumps, and tanks over what would be required with chilled water. As shown in Figure 3 (Kasza and Chen, 1987), depending on the ice loading density, an ice slurry storage tank can be as small as 1/10 the size of a tank used to store an equivalent cooling capacity of chilled water and the delivered coolant flow rate can also be reduced significantly as compared to chilled water. Furthermore, a new pipe system designed for the distribution of ice slurry can be nearly 1/3 the diameter of that required for chilled water delivery of the same cooling capacity. In a retrofit situation using slurry can increase system cooling capacity without upgrading piping and storage tank sizes.

The pipe transport capacity of ice slurry Q, in kJs^{-1} or kW cooling at full melt off, is an important parameter when designing a system with direct application of ice slurry to remote heat exchangers. Figure 4 illustrates the effect of flow rate, ice concentration and pipe diameter on the transportation capacity of ice slurry (Kauffeld et al, 2005).

The storage of ice slurry in tanks is complicated by the fact that under certain conditions the ice particles will, over time, progressively grow together or agglomerate making pumping of the ice slurry out of the tank to loads very difficult (Kasza and Hayashi, 2001b and Hansen et al., 2003). In practice, however, it is always desirable to store ice slurry at the highest ice loading possible in order to most effectively reduce the tank size. When discharged from the storage tank, the ice slurry may sometimes need to be diluted to a lower ice fraction which is compatible with the pump and the piping system in the delivery network Grozdek suggests the optimum ice concentration with regards to pumping power and transport capacity to be about 20 %, as shown in Figure 5 (Grozdek, 2009).

The size of the ice particles, their shape/smoothness, and ice fraction in the carrier liquid can significantly influence the ability to pump ice slurry through piping without particle entanglement, pipe plugging, and causing large pressure drop in ice slurry delivery piping and fittings. As shown in Figures 6 and 7 (Liu et al., 1988; Choi et al., 1988), ice slurry, if correctly made, can be pumped without issues just like water over a wide range of conditions. It is also evident that the pressure drop associated with ice slurry pipe flow compared to water flow is a strong function of particle size and ice fraction even for high quality ice slurry comprised of globular smooth particles. It is well known that the heat transfer coefficients are greatly increased when ice fractions of 15 and more percent are employed (Kauffeld and Christensen, 1997). The heat transfer enhancement is most outspoken at low flow velocities. Also heat transfer is influenced by the ice particle size and therefore depends on the age of the ice slurry.

4.1 Application of ice slurry in building cooling

Compared to other countries, Japan probably has the largest number of installed ice slurry systems (Wang and Kusumoto, 2001). The rough estimate of the number of installations in Japan is over 400 systems, whereas Europe only has approximately 150 ice slurry systems (Rivet, 2009). Most often, ice slurry is only used as an energy storage medium in building air conditioning systems and is not pumped directly to the consumers. The application of ice slurry in air conditioning systems might be beneficial from an energetic point of view when combined with low temperature air distribution systems ($t_{air} \cong 2$ °C). The low temperature air would save fan energy, duct size and hence building height, but the thermal comfort and air quality perceived by working people in the building must of course be ensured. Pumping of ice slurry throughout the building is currently being achieved in at least one office building in Japan. Here the supply air temperature is °C though. The reason for using ice slurry in this building was not saving energy, but saving operating cost, as ice slurry is produced over night and stored in large storage tanks.

In the USA, HVAC is the largest energy consumer in commercial buildings, accounting for over 33 % of total energy consumption. Of this, 13 % is used for cooling and 20 % for other commercial sector building uses. Building cooling is becoming more of a challenge due to the escalating energy costs and the demand to decrease greenhouse gas emissions. Combined heat, cooling and power systems have been growing in application but are having economic problems due to high natural gas and electrical costs and the large upfront capital equipments costs. Operators of large multiple building cooling load systems are frequently constrained by the lack of underground distribution pipelines and coolant storage tank space, and the high cost of tearing up streets to install new piping. Facility operators are often challenged with bottlenecks in their own operations which make it expensive to bring on additional cooling. Finally large scale chilled water systems are capital intensive and use large quantities of frequently scarce water; particularly in the high growth areas of the Southwestern U.S., the Middle East and Asia.

Using ice slurry coolants in HVAC systems can provide more efficient cooling with substantially lower operational and equipment costs. Ice slurry has been recognized for its significant potential to improve cooling capacity over chilled water systems because of the very large heat of fusion of ice (334 kJ/kg). However being able to produce ice slurry with ice fractions approaching 50 % by weight, store it, and then extract it for distribution in a piping network without plugging pipes delivering ice slurry to multiple loads has been elusive and has frustrated the application of this technology.

Figure 8 shows a schematic of a test facility used at Argonne National Laboratory to explore ice slurry production methods involving chemical and thermal smoothing of the ice slurry during production, storage, extraction, and distribution through piping. The tanks shown are ~ 4,000 litres each and the piping is as large as 70 mm diameter.

4.2 Large scale demonstration of district cooling with ice slurry

Ice slurry cooling technology is being adopted by countries such as Japan and Korea to replace chilled water cooling and captive ice storage systems (ice made in a tank which never leaves the tank). These countries have had to address and adjust to high energy costs and seek greater energy utilization efficiencies. The time is now right on a broader scale to utilize ice slurry cooling technology for improving cooling and energy utilization.

A 5 year demonstration program is being developed which will involve supplying ice slurry cooling made in a central plant to multiple buildings on the Argonne campus. Figure 9 shows a schematic depicting ice slurry coolant being made in a central plant and delivered by pipes to multiple distributed site cooling loads. The schematic shows two ways in which ice slurry cooling can be interfaced with a building: For the building on the left, which typifies a retrofit use of ice slurry, the ice slurry never enters the building but cools through a heat exchanger interfaced with the existing cooling system of the building; the building on the right, which typifies a new building designed to use ice slurry, shows a satellite ice slurry storage tank from which the building obtains cooling by circulating ice slurry through the building air handling system.

Upon successful completion, the ice slurry cooling demonstration team and the developed infrastructure will among others have achieved the following objectives:

- Establish a cooling concept which is more energy efficient and yielding operational and equipment cost reductions over current large individual systems
- Develop control and operation philosophy relative to space cooling, district cooling, and the potential for load shifting
- Establish the ability to optimize ice generator design and optimize ice slurry particle conditioning to achieve highly loaded storable and pumpable ice slurry.

4.3 Application of ice slurry in breweries

The Zipf brewery relies on an ammonia plant with ice slurry as coolant for its refrigeration needs. The retrofit from direct expansion ammonia chilling was realised in 2004. The new system was designed to reduce the high energy consumption associated with the old pumping and refrigeration system. The modernisation was undertaken without interrupting operations. The existing refrigeration system was kept, but the coolant loop as well as part of the ammonia pump system was replaced with ice slurry. Most of the existing pipelines were kept, as were the heat exchangers on the beer tanks and in the refrigerated rooms. New installations included two 230 kW refrigeration capacity orbital rod ice generators and air coolers specially designed for ice slurry. A 110 m^3 silo with a refrigeration capacity of 5000 kWh was added to serve as thermal storage. Three Coriolis type mass flow meters determine the ice concentration at different heights. The installed refrigeration capacity was reduced from 1350 kW to 670 kW as a result of load shaving using ice slurry thermal storage. The ammonia charge was reduced from 3000 kg to 500 kg. Several similar systems are known to have been installed in breweries in Japan.

4.4 Application of ice slurry in large kitchens

There are several ice slurry cooling systems installed in large European institutional kitchens in France (Compingt et al., 2009), Germany and Lichtenstein. The hospital kitchen “Klinikum Stuttgart” in Germany belongs to one of the largest ice slurry installations in the industry. The kitchen was built in 2007 and produces up to 6,000 meals a day. Here ice slurry is used exclusively to cool the entire cook and chill process chain including the subsequent distribution system for the first time (Figure 10). This covers everything from recooling vessels and refrigerated rooms to portioning stations and approximately 130 cooled stainless steel tray transport trolleys. Together with induction docking stations and the induction trolleys, reliably cooled transport and gentle regeneration of food are ensured. The plant is designed for a maximum of 9,000 meals per day. Ethanol/water ice slurry is produced in 16 scraped surface ice slurry generators of 185 kW total cooling capacity. The ice slurry is stored in 3 cylindrical storage vessels with a volume of 22 m^3 each. Food is stored in cold rooms cooled by ice slurry admitted air coolers prior to cooking. Depending on the preparation of the food, food is chilled in ice slurry cooled conveyor blast chillers or directly in the large cooking vessels/kettles. This rapid chilling inside the kettle is up to three times faster than the conventional blast chilling and hence provides longer product shelf live. In addition, rapid chilling reduces manual handling, dish washing and food wastage. The chilled food is stored once again in the cooling rooms until it is portioned on plastic trays travelling on conveyor belts. Food which has to be served cold is placed on regular china plates; food which is to be reheated prior to serving is served on china plates with metal coating on the bottom and a plastic cover with a stainless steel inner liner. The trays are placed in insulated double wall stainless steel trolleys holding two columns of 10 trays each. The double wall containers are charged automatically within less than 4 minutes in an ice slurry charging station. The tray transport trolleys keep food cold up to 12 hours, uniformly and HACCP compliant. The tray transport trolley is impervious to impacts and can be washed in cleaning tunnels, cables don’t get in the way while the unit is being moved around and neither waste heat nor disturbing noise is emitted while food is being kept cold. Once at the place of use, induction heating coils are moved in between the trays and heat the food placed on the metal coated china below the stainless steel covered plastic tops, which also are heated by induction efficiently avoiding the formation of moisture condensate. Food placed on regular china or on the plastic tray itself remains cold.

The system results in a complete cooling chain with ice slurry – from the refrigerated room to the refrigeration system, refrigerators and recooling vessels to the food service conveyor belts, plate dispensers and cooling tray transport trolleys. As the ice slurry circuit is self-contained, it produces no waste products harmful to the environment result. There is no need for any additional safety installations. The high-performance ice slurry cooling system generates a uniform low temperature, providing a convincing argument regarding bacterial control. As a result, the ice slurry system completely meets all HACCP requirements.

4.5 Application of ice slurry in truck and railway cooling

A similar system charges trucks with ice slurry before sending the trucks on delivery tour with chilled or even frozen food. Such systems can be found in operation in Japan (Kato and Kando, 2008) and as prototype in Slovenia. Ice slurry is produced at a central plant and is charged into special heat exchangers in the insulated boxes of the truck. The ice slurry refrigeration system operates at a higher efficiency than the standard on-board truck cooling system. Carbon dioxide emissions associated with the refrigeration system could therefore be reduced by 20 to 30 % (Kato and Kando, 2008). In addition, the engine in the ice slurry cooled trucks can be switched off completely at the points of goods pick-up and delivery, therefore reducing noise and exhaust emissions – a feature which is especially valuable in large cities with air quality problems.

China uses ice slurry for cooling of railway cars, where ice slurry is filled in voids surrounding the cargo hold (Wang and Goldstein, 1996). Similar to the 100 year old technology of using block ice, but the ice slurry is much easier to apply.

5. DIRECT CONTACT FOOD COOLING APPLICATION

Over the last five years there have been a large number of installations completed in more than 40 countries for direct contact cooling of various food products. The following text describes the latest development of the direct contact cooling ice slurry technology used in bakery, produce packing, and fishery applications.

5.1 Application of ice slurry in bakeries

Temperature control during dough mixing is essential in any bakery operation. Heat generated during dough preparation may vary depending on the operating conditions of the different products. It has three sources: hydration as the flour and other dry materials absorb water; friction of the mixer motor; and specific heat of individual ingredients. In many cases the ingredient water, even supplied at low temperature, does not contain enough cooling capacity to absorb the excess heat. Flake ice is often manually weighed and applied directly as part of the ingredient to maintain the dough temperature at an optimum level of 25 to 28 °C. Sometimes, CO_2 “dry ice” rather than flake ice is also used for cooling the dough, but this method faces several challenges due to the high operating costs and environmental concerns. In recent years bakery operations are moving towards full automation and the manual handling of ice is becoming more and more a bottleneck issue for many bakery processors.

Ice slurry technology offers an effective solution for dough cooling. Figure 11 shows a principle diagram of an ice slurry system. Using a water-salt-solution as the ice making medium, crystals are formed inside the ice generator, and are then pumped into a static ice storage tank where they remain suspended in water. Through an ice harvesting mechanism on top of the tank freshwater based ice particles are discharged on demand, and are mixed with chilled water in a mixing tank to form slurry. They are then delivered directly to the dough mixers through a closed loop. Metering pumps at each delivery location can precisely control the amount of ice slurry from the loop to the mixers.

There are a few ice slurry installations in North, Central and South America for preparation of various dough products from white bread, sweet bread to baguettes. Depending on the ice concentration requirement, the ice remixing and delivery set-up may differ slightly from the above diagram. In one installation, only dry ice particles are applied into the dough mixer.

Installations confirmed that ice particles either in the slurry or in the dry form are easily mixed and distributed in the dough ingredients, evenly control the dough temperature, and eliminate the need to over knead the dough. They result in better and consistent dough texture and quality. One processor for white bread noticed that using crushed ice or flake ice often ended up with sticky dough, affecting the gluten quality and resulting in a bad appearance of the crumbs. When using ice slurry particles homogenous and regular size of alveolus is observed in the produced slices of bread. These conclusions are still qualitative in nature and further scientific investigation is required.

5.2 Application of ice slurry in produce packing

For many fresh vegetables, preserving product quality is dependent on rapid and thorough cooling immediately after harvest and maintaining a low temperature environment during storage or processing. Ice slurry is an effective post-harvest cooling medium for a variety of commodities including asparagus, cauliflower, broccoli, green onions, cantaloupes, leafy greens, carrots and sweet corn. Take broccoli as an example. Rapid icing by ice slurry to the field-packed, waxed broccoli cartons after harvesting prevents wilting, suppresses enzymatic degradation and respiratory activity; slows or inhibits the growth of decay-producing micro-organisms, and reduces ethylene production. It ensures that broccoli heads are retained in a fresh and attractive condition throughout the cold chain, right to the consumer.

There are several ways to charge ice in the carton packed with a variety of produce. The simplest icing method is to add a measured amount of ice manually to the top of each carton. This method is labour intensive and is only marginally acceptable for small-scale operations. Uneven cooling of produce is quite common in this case, because ice generally remains where it is placed until it has melted.

Using ice slurry to cool and preserve produce is a preferred method for the modern produce packing operation. It is particularly effective on dense and palletized packages. A widely used approach is to inject ice slurry into palletized produce cases manually through the hand openings. It is a simple but low efficiency method, since it takes 5 minutes for two dedicated workers to ice a pallet of 30 cases (Boyette and Estes, 2000). Using an automatic pallet icing chamber design can greatly improve the icing efficiency. The design includes a stainless steel enclosure capable of handling a pallet of 48 cases (9 kg broccoli per case) during each icing operation. Only one operator is required to move the pallet into the chamber. Once a locally positioned icing switch is turned on, two front doors are closed automatically. A circulation pump begins to move ice slurry in the mixing tank located right underneath the chamber to the top of the enclosure, where it is distributed to four vertical slots built on the side walls. Ice slurry is then forced to flow through the hand openings and fill the voids throughout the cases within 90 seconds. As water drains off, ice particles are tightly packed with the produce. The pallet is then moved out of the chamber.

In order to allow produce packers to optimally adjust icing quantity in produce cases based on their shipping destination, an immersion type of the icing mechanism was developed and was implemented in a large produce packer in California for the broccoli packing. The new mechanism includes a 48 case pallet holder, a hydraulic driven lift, and a 17.5 m^3 immersion tank where ice slurry is maintained homogenously through two 7.5 kW agitators. By varying the dip time each pallet stays in the immersion tank from 45 to 120 seconds, ice quantity charged into each broccoli case can be regulated from 5 kg to 13 kg.

5.3 Application of ice slurry in fishery

5.3.1 Current status—As a highly perishable food, fish begins to deteriorate rapidly as soon as it dies. Without proper product preservation, bacterial, enzymatic and chemical processes quickly reduce shelf life, cause drip loss, and ultimately result in product rejection through spoilage. The deterioration process is accelerated by elevated temperatures; by damage such as bruises, cuts and scrapes; and by contamination. The key to fish preservation is immediate chilling upon catch or harvest to a temperature slightly above the freezing point and maintaining this temperature throughout the cold chain.

Ice slurry as a new technology to maximize the chilling speed of fish has received great attentions over the past 25 years. The Department of Fisheries and Oceans of Nova Scotia, Canada was the first organization that conducted a systematic study from 1984 to 1988. It published a series of reports on workability, physical characteristics and cooling effects of ice slurry on fish. Subsequently, fishery institutions around the world like Sea Fish Industry Authority of UK, Norwegian Herring Oil and Meal Research Institute, Icelandic Fisheries Laboratories, and lately, Institute for Marine Research of Spain have conducted in-depth analyses and trials on ice slurry for various fish species. After almost 30 years of continuous efforts from the manufacturers and research organizations, ice slurry is now well recognized not only as an incomparable cooling technology, but also as an excellent preservation medium. It has been incorporated in many newly published fish handling guides and regulations. For example, the latest series of seafood industry quality guides launched by The Irish Sea Fisheries Board (2007) outline the best icing practices for whitefish as follows:

- Slush icing is important for certain species e.g. tuna, targeting premium markets;
- Slush ice ensures fast and even chilling of the fish, as it gives better contact with the surface of the fish compared to traditional icing;
- Slush ice also minimizes bruising or pressure damage as it is a liquid medium.

Today, there are over 700 systems installed in the fishery, making the fish industry one of the largest markets for the ice slurry technology. Iceland, Japan and Norway are top three countries on the list. Ice slurry is increasingly used for chilling, storage and transportation of fish onboard fishing vessels and barges, at farms, and inside processing plants. Success has been reported for almost all major fish species such as tuna, yellowtail, salmon, cod, haddock, hake, herring, mackerel, sardine, shrimp, mussel and lobster (Wang and Goldstein, 2003; Piñeiro *et al.*, 2004). Under the current negative global financial environment ice slurry will be needed more than ever by the fish processors and fishermen to gain operational efficiencies and improve product quality.

5.3.2 Challenges and Solutions

Quality and Yield: One of the most challenging demands faced by the fish industry is to improve the quality and yield of the fish products. Recent publications with support of microbiological, biochemical and sensorial analyses suggest that ice slurry is a promising technology to achieve that goal for a wide range of fish species (Piñeiro *et al.*, 2004). For example, Rodríguez et al. (2005) showed that storage of horse mackerel in the brine based ice slurry led to a substantial enhancement of shelf life, from 5 days with flake ice to 15 days. It also involved a significantly slower formation of total volatile basic nitrogen (TVB-N) and trimethylamine nitrogen (TVM-N) after 8 days of storage. Similar inhibitory effect on quality loss mechanisms were also reported for sardine, with an increased shelf life of 15 days in ice slurry as compared to 8 days in flake ice (Carmen *et al.*, 2005). Ice slurry was also found to help increasing the yield of fish and fish fillets. Research by the Norwegian Institute of Fisheries and Aquaculture discovered that cod placed in ice slurry for three days (the maximum allowable time for such storage) became on average 4 % heavier without any change in quality (Joensen *et al.*, 2001). In contrast cod stored on ice alone did not gain any weight. According to Piñeiro *et al.* (2004), the presence of sodium chloride in the ice slurry at concentrations similar to those found in marine water exerts double effects, namely, a higher preservation effect, and stabilization of the myofibrillar protein fraction implying larger yields during storage, filleting or freezing.

While the spoilage rate of fish is considerably slowed down in ice slurry, some fish species like sea bass are reported to exhibit cloudy eyes in the brine based ice slurry, negatively affecting the appearance and quality of fish (Piñeiro *et al.*, 2004). This is probably due to the precipitation of an eye component at subzero temperature level, at which most of the current ice slurry systems are operated. Ice slurry produced from seawater may also create problem of salt uptake during extended storage of some fish species like pelagic fish. The challenges are to identify the optimal cooling and storage condition for each fish product, and then design a system that can accurately control the temperature and the salinity of ice slurry to a certain level suitable for each application.

A variable-state ice slurry system offers attractive features to address the above issues in the fishery. The heterogeneous ice storage design allows separation of ice particles with the brine inside the ice storage silo, as shown in Figure 12. Ice particles accumulated at the top of the tank can then be discharged upon request, mixed with a controlled amount of chilled water and/or brine to form pumpable ice slurry with any required ice concentration and salinity.

Mobility: As the awareness of using ice slurry to preserve catch in any scale of fisheries grows, there is an increasing demand for mobile ice slurry systems that can be delivered as completely self-contained units, in some cases even including diesel power generators. Mobility is especially important for remote areas with little or no infrastructure and where processing of large volumes of fish takes place seasonally.

To meet market demands, containerized ice slurry systems have been designed for both land-based and onboard fish processing operations. The ice slurry generators equipped with their own refrigeration system, a pumping and control station, sometimes also an ice mixing/storage tank are pre-installed in a standard ocean going ISO 20’ container and factory tested before shipment. Space is limited in the container and compact design sometimes becomes a challenge. However, the benefits of the containerized system to the customer are enormous. Besides its mobility, it also allows easy connection to the municipal electric power and water supply, removes requirement for dedicated machine room, and greatly reduces installation time and cost. While small systems with up to 100 kW ice slurry production capacity are often accommodated within one 20’ container, larger systems can be built up in one 40’ container or multiple containers.

Automation: One of the most attractive features of ice slurry is its pumpability. This eliminates the need for costly means of mechanical or labor intensive ice transportation and substantially reduces operating and service costs as the distribution system is fully automatic. The demand for higher operational efficiencies and better cold chain management has created pressures for more innovations in automation. One of the latest developments is computer based monitoring and control systems. These measures improve stability and reliability of the system. Moreover, it can be easily integrated into the customer’s quality control system for the cold chain management throughout their operation.

5.3.3 Installation Example—

Seafood quality starts from the catch. There has been a trend towards more ice and refrigeration units onboard fishing vessels lately. This results in more ice slurry installations for the onboard sector. About 70 to 75 % of the total ice slurry installations in the fishery are for fishing vessels of various sizes and types. A recent development in the onboard application is the introduction of a low salinity ice slurry system. The system was delivered to Hokubu Makiami Gyogyo Inc. of Japan in 2006, and was installed aboard its 300 tonne purse seiner “Hokusho Maru”, which fishes tuna or skipjack from April to October, and mackerel and sardine from November to February.

Figure 12 shows a principle diagram of the ice slurry system. It has 90 kW ice making capacity and includes a compact ice storage silo. During the 25 hours or longer period from the port to the fishing ground, the ice machine cools the seawater down to the freezing point, and then produces ice particles in the slurry form. It is then delivered to the silo where ice and water separation takes place. Ice particles are then discharged and mixed with seawater in an auger tank to form slurry with 50 % ice concentration, which is delivered to several 25 m^3 fish holds. Upon catch, warm tuna is loaded immediately into the fish holds. As cooling takes place, ice melts and seawater is then removed from the holds, and fresh ice slurry is further added into the fish holds. The same procedure repeats until the fish temperature reaches 0 °C.

The ability of adjusting the ice concentration up to 60 % and the salt content in the range of 2 to 3 % in the ice slurry ensures maximum preservation results without damage to delicate fish and avoids excessive salt uptake by the fish. According to the company’s division manager, the fish caught can be chilled quickly onboard, so that its freshness is better preserved, when compared with fish chilled with crushed ice. In addition, it does not hurt the surface of the fish and it also saves labor.

6. ICE SLURRY MEDICAL COOLING

In 2000 Argonne engineers and University of Chicago (UC) Medical School doctors/researchers started developing ice slurry medical cooling, for inducing protective hypothermia in critical organs (Becker and Kasza, 2000). Recently UC and Argonne have formed a Bioengineering Institute for Advanced Surgery and Endoscopy which is expanding ice slurry cooling for inducing highly targeted protective cooling for a wide range of surgical applications.

Surgical procedures are pushing the limits of technical excision and becoming less invasive through the development and use of laparoscopic procedures assisted by surgeon/machine robotic manipulations. There is an unmet need to protect critical organs and various tissue masses through the course of surgical manipulations.

6.1 Why Ice Slurry Medical Cooling?

Medical ice slurry protective cooling is based on the premise that the ability of organs, tissue, and neurology to survive ischemia, reperfusion damage, and surgical insults is improved by cooling rapidly in 5–15 minutes 4–15 K, (depending on organ), below the normal temperature of 37 °C. Cooling slows cell chemical processes; namely metabolism and reduces the need for oxygen which slows cell death providing more time for medical treatment. Presently cardiac and cardiovascular surgeons often use bypass heat exchangers to induce protective cooling which is slow to implement and quite invasive (sometimes causing “bypass brain”). External cooling with ice packs, blankets, caps and jackets is also sometimes used for inducing protective hypothermia. However external cooling is very slow ($< 0.03\ \mathrm{Kmin}^{-1}$) and similar to bypass methods cools the entire body often causing adverse secondary effects such as uncontrolled shivering or arrhythmias. Global cooling also frequently fails to protect a specific organ from ischemia because of failure to achieve the temperature believed to be most protective for that organ.

Chilled single phase saline is starting to be used for inducing medical cooling. However it is not capable of inducing the rapid targeted cooling that is possible with ice slurry. Ice slurry has the additional benefit of absorbing more than four times the heat than chilled saline because of the ice particle melting, (change of phase). Thus a much smaller quantity of ice slurry is required to cool to the same temperature as a single phase coolant, which relies only on sensible heat absorption. This characteristic of ice slurry greatly reduces the chances of upsetting bio-system chemistry resulting from coolant overload. Finally, ice slurry cools the target tissue faster than saline because the ice slurry remains at ~ 0 °C until all the ice is melted whereas the saline immediately from its entry into the delivery catheter starts increasing in temperature. Thus at the target, the temperature gradient between tissue and coolant is much larger for ice slurry than for saline and the tissue cools much faster. Additionally the very small ice particles flowing over the target tissue increase the convective heat transfer coefficient between coolant and tissue to higher levels than with single phase chilled saline.

For medical applications, ice slurry in its most elemental form consists of specially engineered ice particles of less than 0.1 mm size suspended in a biologically compatible carrier liquid containing chemicals for smoothing the ice particles and beneficial to cell health. The ice slurry is produced using a carefully controlled production process to achieve maximum ice loading and trouble free operation developed by Argonne. When the ice particles in the most basic medical saline slurry melt due to absorbing body heat, the remaining liquid phase has the salinity of standard medical drip bag saline solution, which is compatible with body chemistry. Various chemicals or gases, depending on application, can also be added to the ice slurry as “cell health enhancers”. Recently Argonne equipment has been used to make ice slurry from a commercially available blood substitute called Hextend. Ice slurry made with commercial blood substitutes allows protective cooling as well as cell nourishment to be introduced simultaneously.

6.2 Ice Slurry Medical Cooling Applications Being Developed

Currently five ice slurry protective medical cooling applications, described below, are being developed.

6.2.1 Cardiac Arrest Protection—Cardiac arrest (sudden stoppage of heart function) strikes about 1,000 people a day in the United States. The current survival rate for sudden cardiac arrest occurring outside of a hospital is less than 5 %. After ~15 minutes without oxygenated blood flow, brain cells and those of other vital organs such as the heart begin to die rapidly. If paramedics fail to restart the heart quickly by defibrillation, then brain loss becomes significant. However, cooling of cardiac arrest patients by 4 K below the normal body temperature of 37 °C after failed defibrillation is believed to be of significant benefit.

The first medical protective cooling application explored by Argonne and UC was for out-of-hospital emergencies resulting from cardiac arrest. For this application, the ice slurry is delivered to the lungs, without ever coming in contact with the blood, and cools the blood circulating to the brain and heart. Cooled blood flowing through the brain and heart reduces the damaging effects of oxygen deficiency by inducing cooling (therapeutic hypothermia). Upon ice slurry melting, the residual saline solution in the lungs is removed by a suction tube. In the future, treating cardiac arrest with ice slurry will involve the following three steps performed by paramedics:

Step 1 After defibrillation fails, paramedics deliver one to two litres of ice slurry through an endotrachial (ET) tube inserted into the lungs.

Step 2 Immediately chest compressions are initiated to circulate cold blood to the brain/heart; cooling quickly 4–5 K below normal and protecting for up to one hour.

Step 3 Medics rush the patient to an Emergency Room where hopefully the heart can be restarted.

Experiments conducted at UC using a large swine (50 kg) model of cardiac arrest have as shown in Figure 13 proven that ice slurry coolant can effectively decrease the temperature of the brain and heart by 4 K in 10 minutes which is protective.

6.2.2 Minimally Invasive Laparoscopic Kidney Surgery Protective Cooling— Conventional open-cavity kidney surgery involves a long incision made in the abdomen. In order to minimize the amount of blood lost during the surgery the renal artery and vein are clamped before cutting the organ. Without cooling, kidney ischemia damage will occur if the clamping lasts for more than 30 minutes. To reduce ischemia damage in conventional surgery, the surgeon uses a sterilized glove to hand pack ice chunks around the organ. Cooling with ice allows the surgeon to induce protective hypothermia thereby reducing ischemic damage and extending surgery time significantly beyond thirty minutes. In recent years, minimally invasive laparoscopic procedures are rapidly being developed to replace open-cavity surgery. Even though laparoscopic kidney surgery reduces scaring and post-surgical recovery time, the procedure is currently hindered by the inability to cool the organ due to lack of access for hand packing with ice. Research is underway to adapt ice slurry cooling technology for use in laparoscopic surgeries (Laven and Kasza, 2006, Kasza et al., 2006).

Laparoscopic surgery replaces the long abdominal incision in open-cavity surgery with three to four small incisions through which small access ports are inserted. These ports allow instruments to be inserted: one of which is a fibre optic endoscope/light source for viewing the patient’s organs and surgical manipulations on a video monitor. The other ports are used for the access of surgical tools for clamping, cutting, suturing, and now for supplying pumpable ice slurry for cooling. As shown in Figures 14 a and b, ice slurry cooling involves using an engineered delivery tube inserted in a laparoscopic port for delivering and coating the outer surface of the kidney.

After the renal artery and vein are clamped, the kidney is then cooled to below 15 °C and the surgery begins. Animal data in Figure 15 shows that the kidney is quickly cooled for over 90 minutes; which significantly extends available surgery time. After the surgery has been completed, the kidney warms quickly after unclamping and the melted or remaining ice slurry is removed through a suction tube.

6.2.3 Protective Cooling During Cardiac Surgery—Recent research has shown cooling the heart can be protective (Otake et al., 2007). Argonne engineers and UC cardiac surgeons are developing improved cooling procedures using ice slurry and the associated ice slurry production/delivery equipment for inducing heart muscle protective cooling. One heart cooling application being developed involves protecting the heart from reperfusion damage as a result of balloon angioplasty opening up a blocked artery. Animal model testing involves the surgical intervention with no protective ice slurry cooling and then with ice slurry protective cooling induced in several ways. Figure 16 shows a 100 cm long cardiac catheter of 1mm ID delivering ice slurry for protectively cooling the heart.

An initial assessment indicates that the ice slurry delivery flow rate required to keep the entire heart at a protective 32 °C with ice slurry delivered from the left and right coronary artery is 16 $\mathrm{ml min}^{-1}$ having 50 % ice loading. To avoid possible arrhythmias associated with the inducement of myocardial hypothermia it is current conjecture that the myocardial temperature should not be cooled to lower than 32 °C. Scoping calculations have also shown that cooling and maintaining the heart myocardium at a protective temperature with ice slurry requires only 1/3 of the volume of chilled saline. This gives ice slurry cooling a significant advantage since a smaller volume can be used to maintain the desired protective temperature, thus reducing the chance of bio-system overload.

6.2.4 Minimizing Spinal Cord and Brain Neurological Damage—Argonne engineers, UC neurocritical-care doctors, and vascular surgeons are exploring how ice slurry can be used to protectively cool the spinal cord and brain from ischemia, reperfusion injury, and neurological impairment. An assessment of current literature reveals that protective cooling in this medical arena is receiving much attention world wide. The literature suggests that there is a need for developing much more potent and easier to use cooling methods in order to realize the benefits of targeted cooling. Ice slurry coolants have the potential for satisfying this need. It has been established that catheters can be used to deliver ice slurry to the brain via arterial or cerebral spinal fluid (CSF) routes and to the spine. Some of these catheters are smaller than those used in cardiac surgery.

6.2.5 Improving Organ Recovery–Transplantation—The goal of this research is to explore the potential of using ice slurry cooling for protecting and improving organ recovery viability outcomes. Ice slurry cooling has the potential for improving organ viability by protecting against warm ischemia. This intervention, if proven, will allow recovering non-heart-beating donor organs of higher viability (reduced ischemic damage) and would constitute a significant advancement in making more organs available for transplantation.

Current day technology involving infusing cold liquids into the femoral artery results in a slow organ cooling-rate compared to direct perfusion cooling of the isolated organ normally done for recovering organs from a heart beating donor. Slow cooling leads to impaired organ function and limited clinical interest as a result. Efforts are underway to develop protocols for using ice slurry coolants to overcome the existing limitations of cold single phase coolants and improve the number of organs available and their viability. One approach being explored involves delivering ice slurry cooling through ports similar to those successfully used in laparoscopic kidney surgery (Laven and Kasza, 2006). A second scenario being explored involves using the procedure being developed for cooling the heart during cardiac arrest by filling the lungs with ice slurry combined with the procedure used for protecting the kidney during laparoscopic kidney surgery. This protection scenario has the potential for protecting all donors organs located within the trunk of the body.

7. CONCLUSION

There are many more ice slurry applications around the world. This article provides some examples of how ice slurry technology has been used and gives an impression of the breadth of the technology.

Compared to the centuries old conventional vapour compression refrigeration technologies, the commercial use of ice slurry cooling started just about 25 years ago. Ice slurry has great potential for the future. Ice slurry makes it possible to use indirect refrigeration systems with small amounts of charge of the primary refrigerant. In addition, ice storage tanks enable load shaving and can result in operating cost savings. Furthermore, the use of ice slurry provides the possibility for direct contact cooling or freezing of food products and for saving human lives by protectively cooling organs.

With the improved understanding of how the micro-scale features of ice particles, which comprise ice slurry, influence the engineering macro-scale behaviour of the ice slurry and how to control these small features during slurry production, ice slurry cooling can be used more broadly in the industrial sector as well as for new applications such as inducing targeted medical protective cooling. In all applications however, engineering creativity and strict attention to design details must be practiced in order to achieve trouble free system operation while avoiding ice slurry agglomeration, distribution system plugging, and minimizing pumping power requirements. Additionally, careful attention must be paid in choosing the right ice slurry generating method such that the ice slurry produced is suitable for a given application.

In today's challenging market customers pay attention to only those technologies that bring substantial measurable value to their operations through cost savings, improved productivity and quality, reductions in waste or emissions and in the case of medical cooling improving the ability to save lives. Installations in various cooling applications described above confirm that ice slurry is an adaptable cooling and sometimes also a preservation medium and its benefits can be maximized through innovative system designs for ice production, storage and transportation for each specific application. The future of ice slurry technology depends on how successfully the following issues will be addressed:

- Product development. The ice slurry generator should remain the focus of any new development. Machines with less maintenance, higher COP, and lower costs are required to compete with the traditional technologies.
- For medical applications the new considerations/parameters associated with the ever broadening use of ice slurry must be factored into the equipment design in an optimized manner with the medical professions needs guiding all developments.
- Appropriate control strategies suited for ice slurry systems are needed; A key technology is the precise measurement of the additive as well as ice concentration.
- Ice storage tanks need further research in order to minimize the energy used for keeping a tank homogeneously agitated and/or to prevent ice agglomeration especially at the top of heterogeneous storage vessels.
- Application study. There are only limited studies reported on cooling and preservation with ice slurry for some fish species and broccoli. More investigations are required to cover a wider range of direct contact cooling applications, for examples, the use of ice slurry for the cooling and preservation of valuable fish species like tuna, for the cooling of pre-cooked soup and sausages.
- Marketing. While ice slurry has good market awareness in industries like fishery and building air-conditioning, it is not well known in other food product process cooling. Continuous efforts will be necessary to promote the benefits of the technology through different channels.

Through a close collaboration among manufacturers, research organizations and end users, it is believed that ice slurry technology will enjoy much wider application in the near future.

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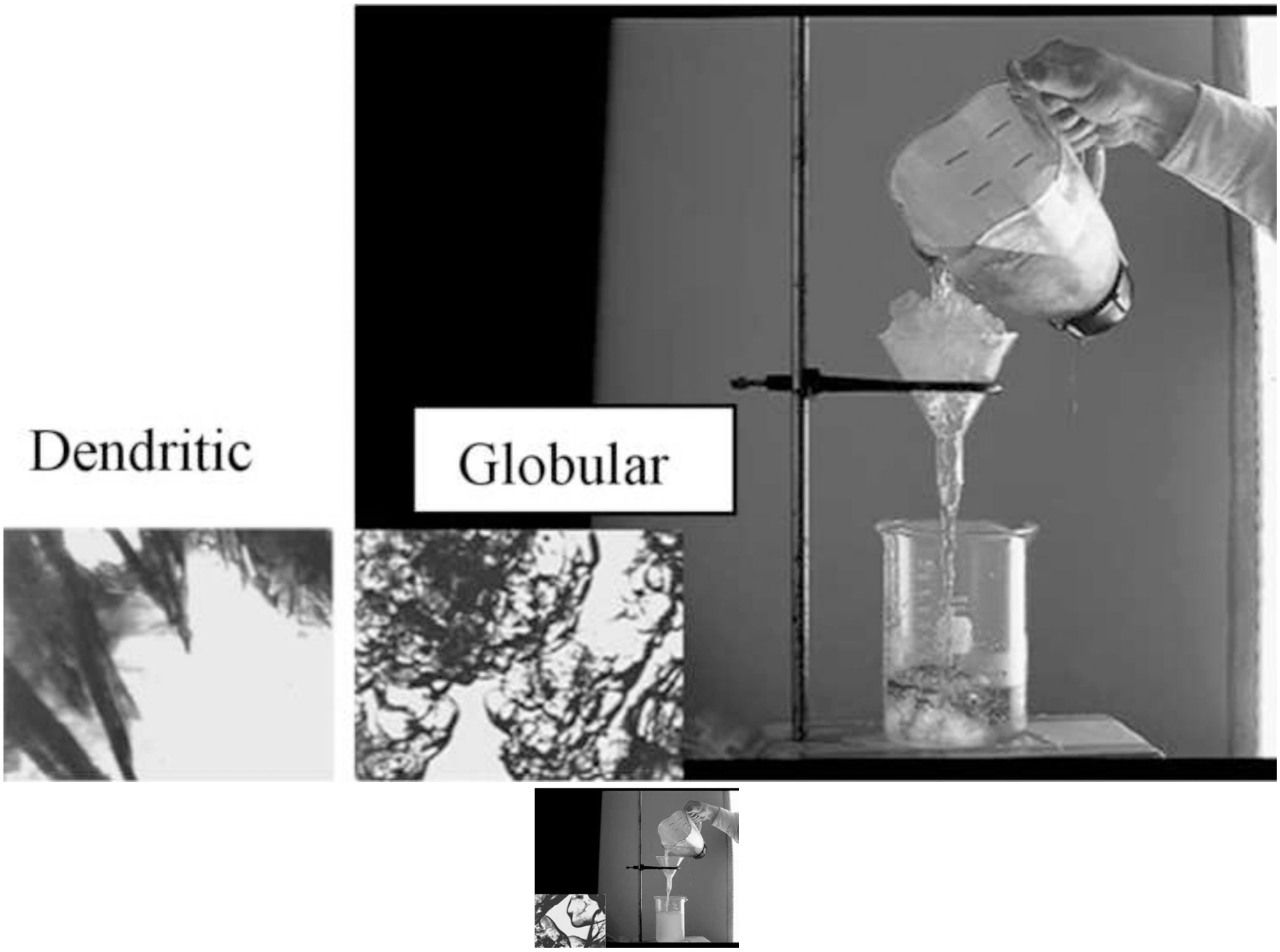


Figure 1.
Chemical and thermal smoothing of globular and dendritic ice particles yields dramatic improvements in ice slurry behaviour: (a) no smoothing; bad ice slurry; (b) with smoothing; good ice slurry (Kasza and Hayashi, 2001).

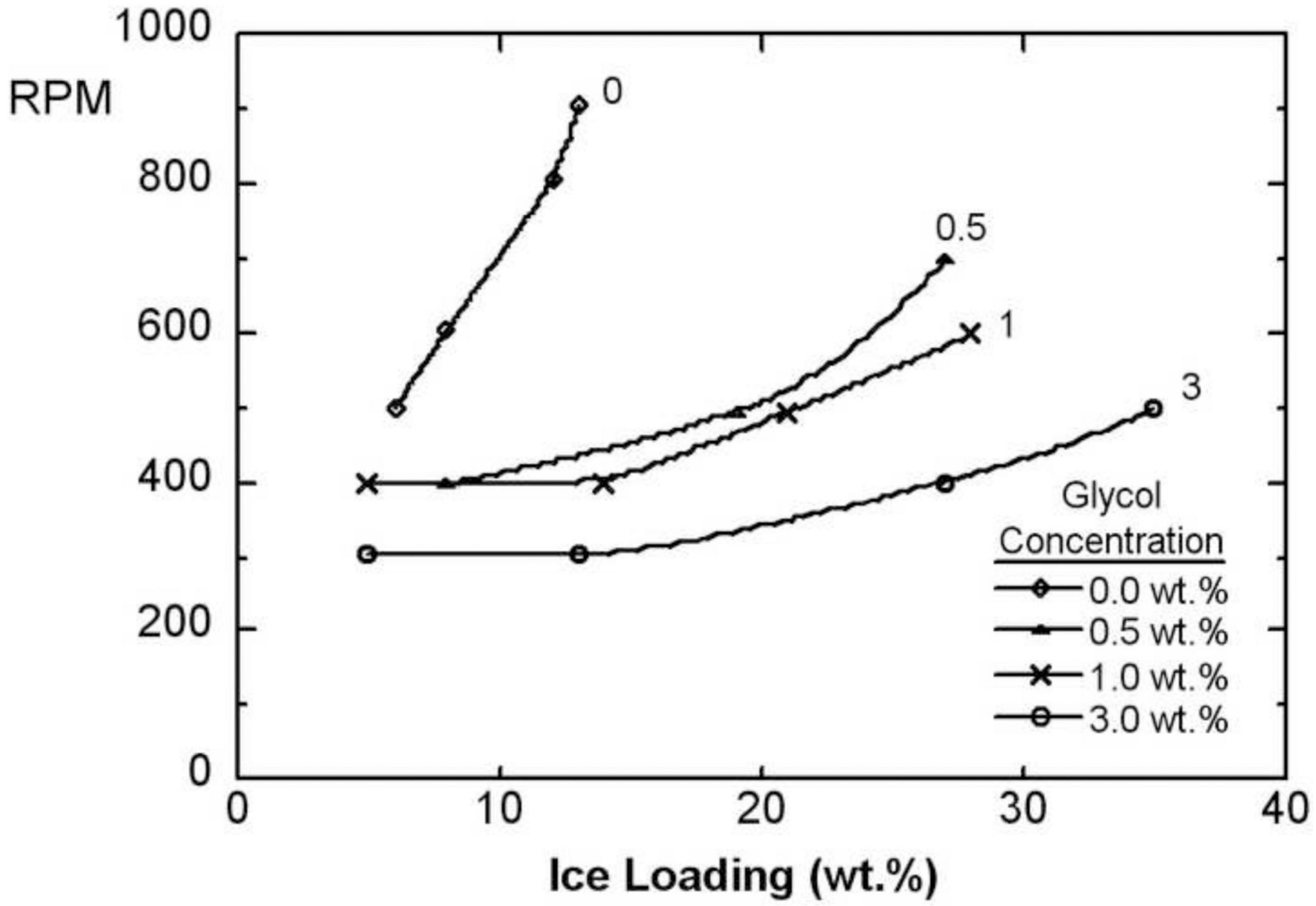


Figure 2.
Chemical smoothing and mixer rpm required for mixing crushed ice particle slurry (Kasza and Hayashi, 1999).

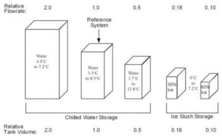


Figure 3.

Comparison of coolant flow rate and storage tank volume for ice slurry and conventional chilled water (Kasza and Chen, 1987).

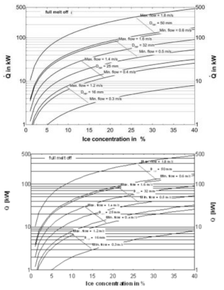


Figure 4.

Transport capacity of ice slurry (kW of cooling at full melt off) in pipes ($D_{rør}$: Inner pipe diameter) (Kauffeld et al, 2005).

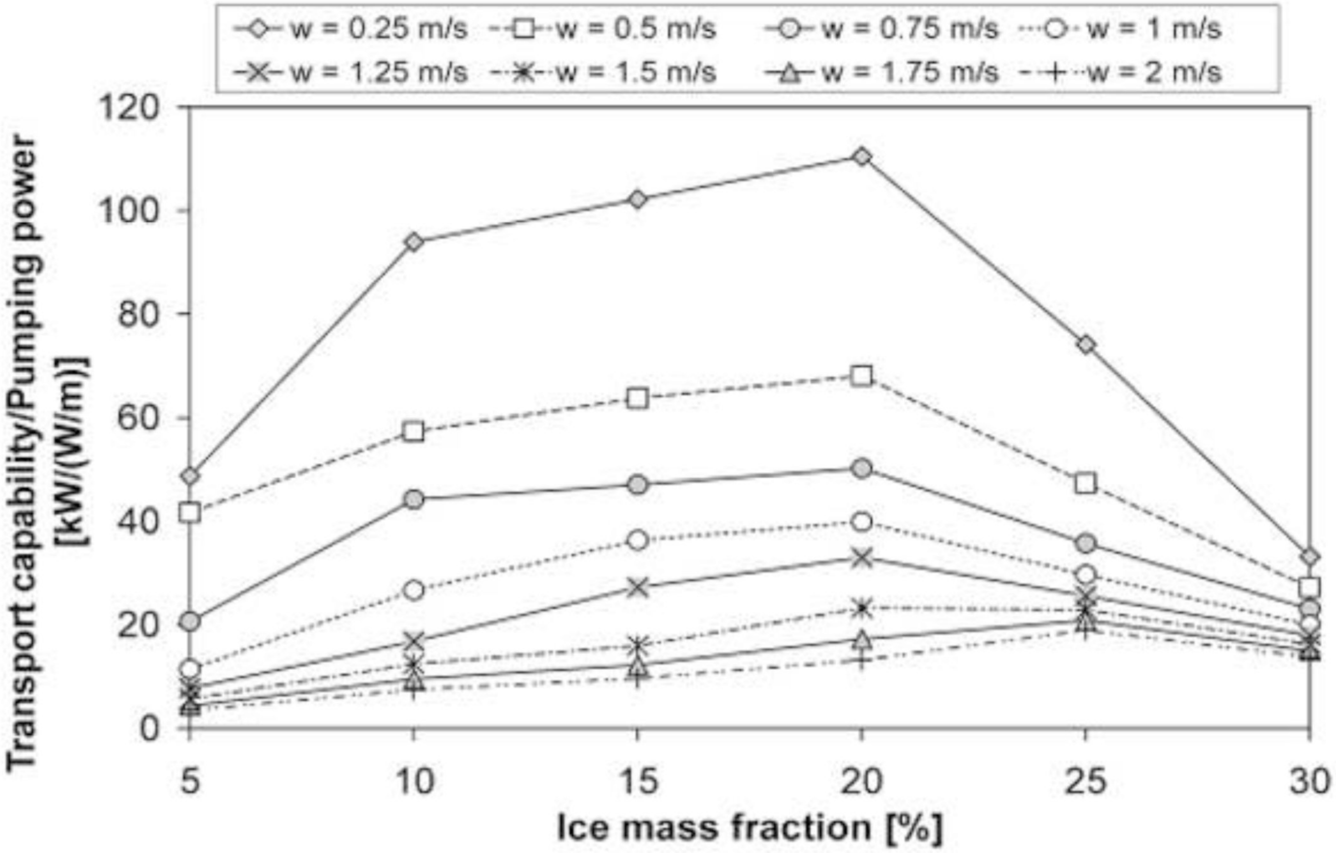


Figure 5.

Ratio of ice slurry transport capability and required pumping power versus ice mass fraction for 15 mm tube (Grozdek, 2009).

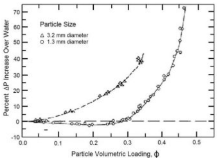


Figure 6.

Influence of particle size and ice fraction on pipe pressure drop; ice slurry versus water (Liu et al., 1988; Choi et al., 1988).

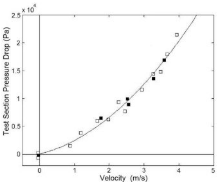


Figure 7.

Pressure drop in a 7 meter long, 50 mm internal diameter pipe: ice slurry (18 % ice loaded; solid symbol) and water (1 °C; open symbol) ; (Liu et al., 1988; Choi et al., 1988).

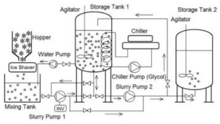


Figure 8.
Schematic of Argonne ice slurry facility.

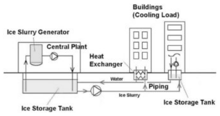


Figure 9.
Schematic of distributed-load ice slurry building cooling system.

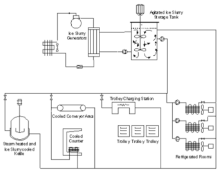


Figure 10.
Schematic layout of an ice slurry system similar to Klinikum Stuttgart.

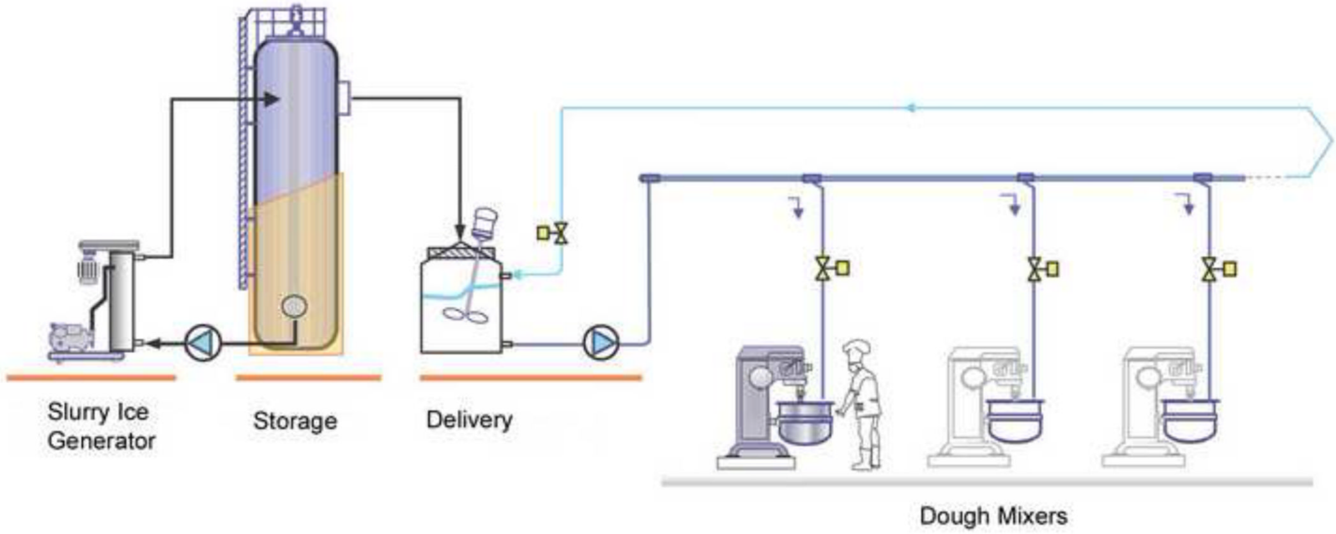


Figure 11.
Principle diagram of an ice slurry system for bakery application.

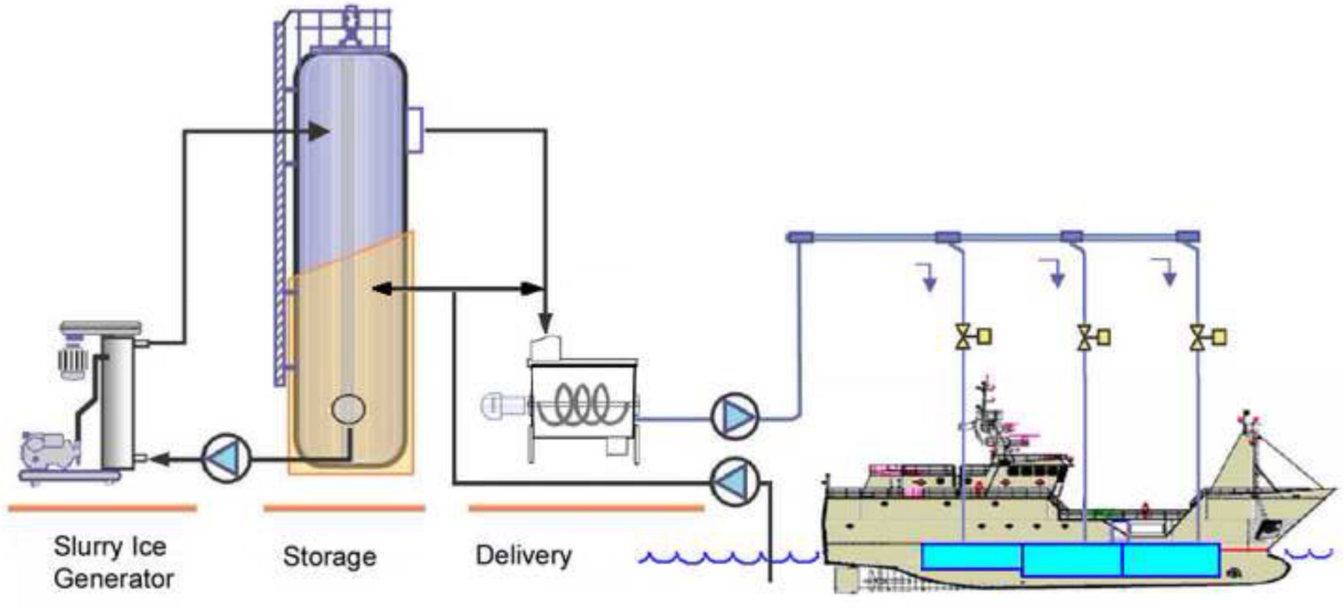


Figure 12.
A low salinity ice slurry system used onboard a Japanese purse seiner.

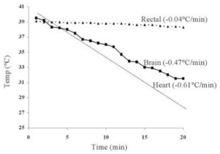
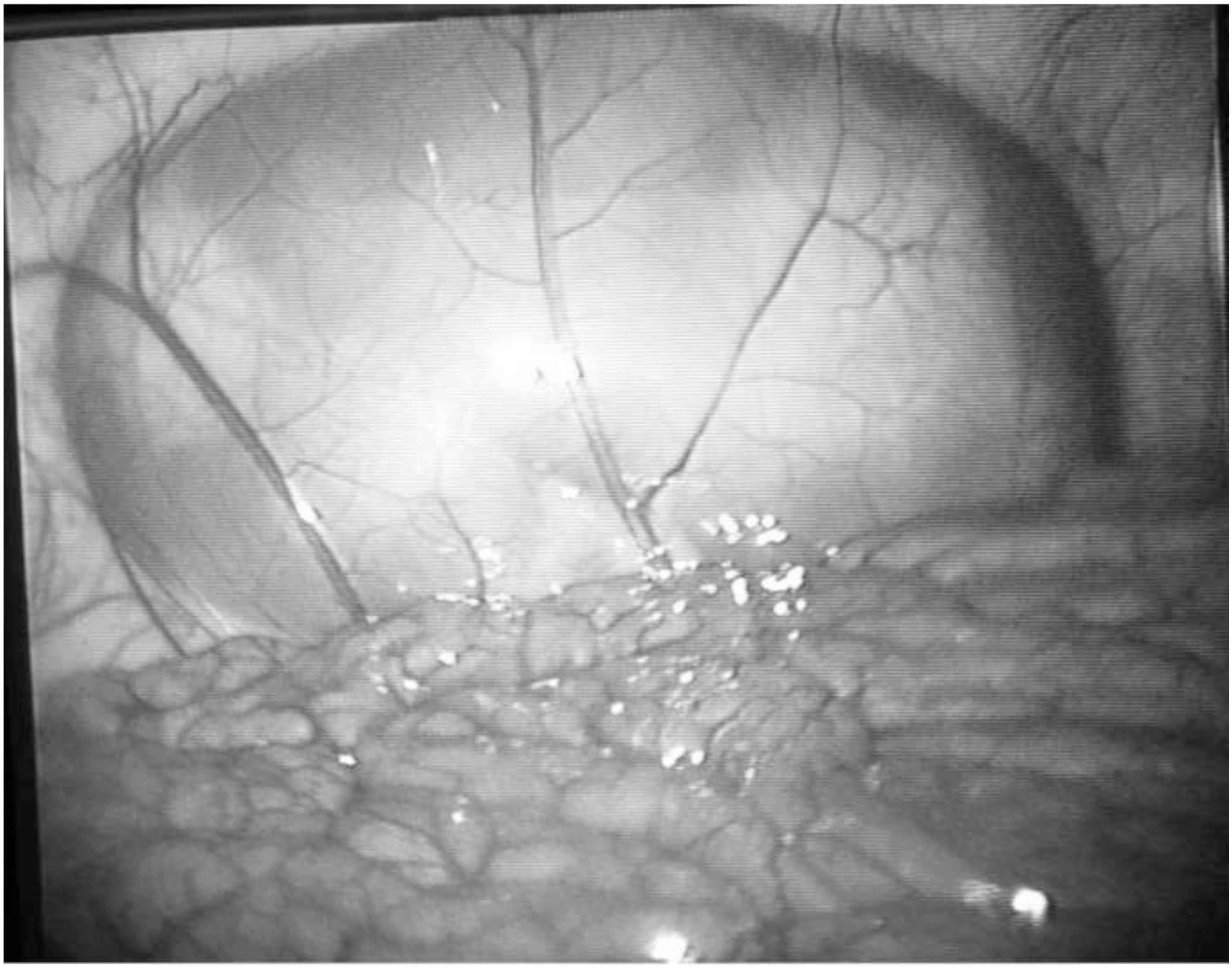


Figure 13.
Slurry cooling of brain and heart during cardiac arrest.



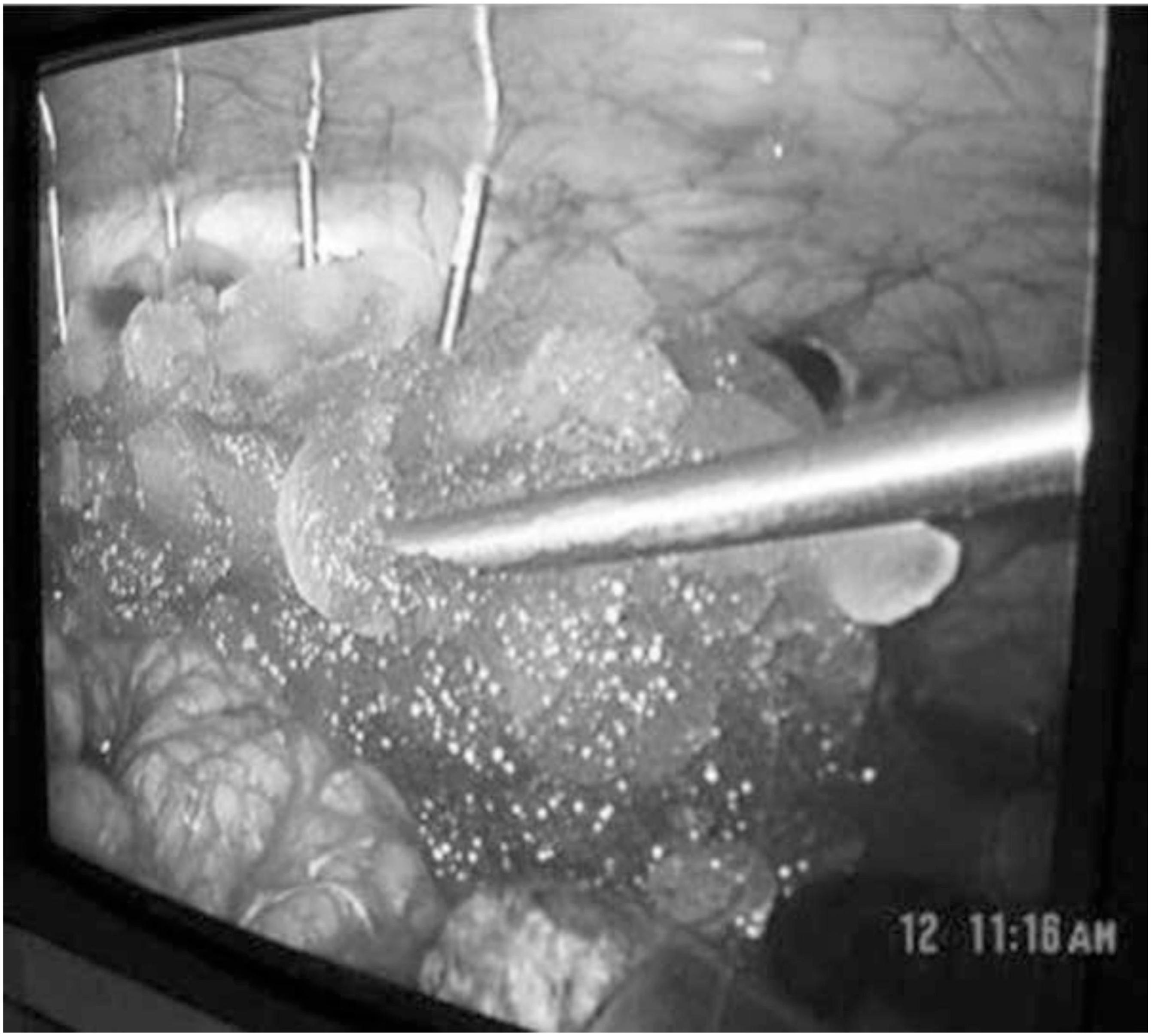


Figure 14.
a, b: Endoscope view of kidney a) before being covered with ice slurry and b) after coating the external surface with ice slurry: protects kidney for > 90 min

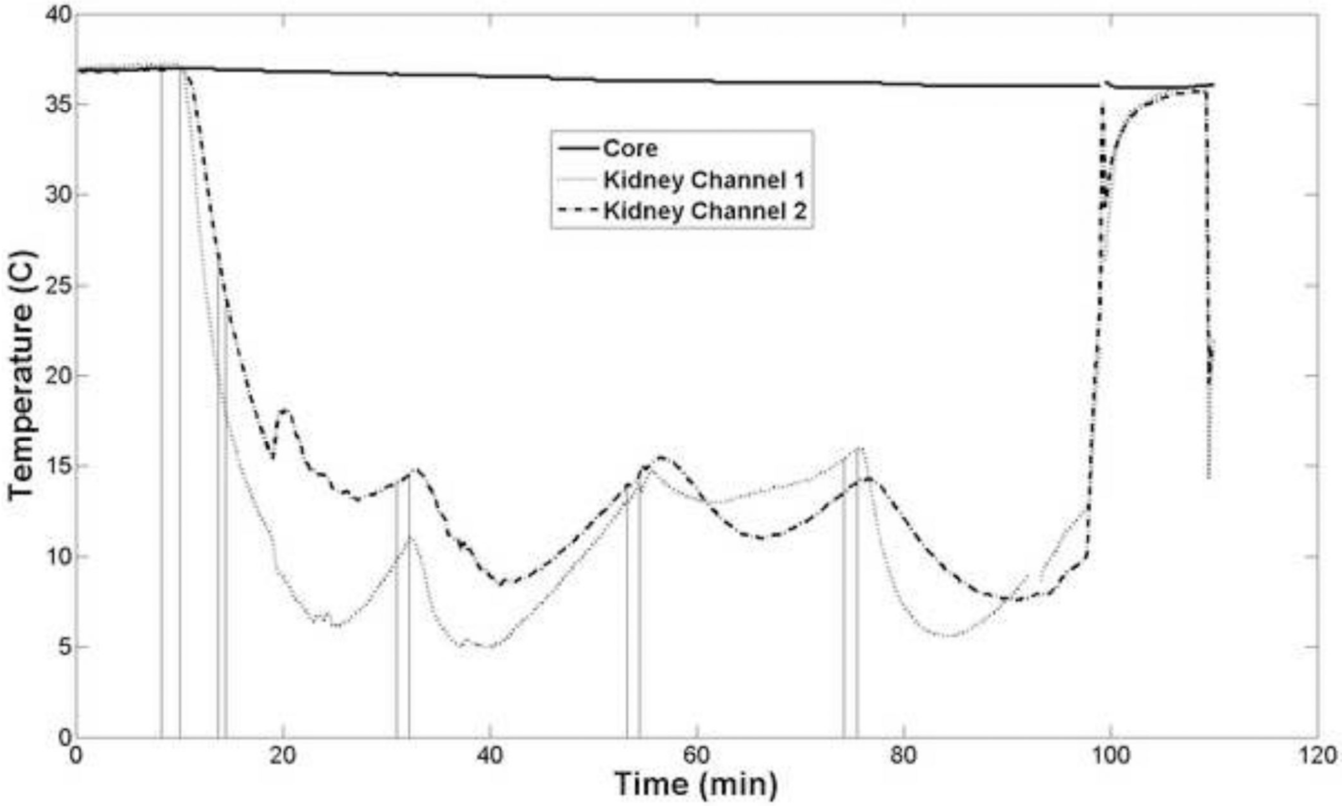


Figure 15.
Temperature of kidney cooled with ice slurry for protection during 90 minute surgery.

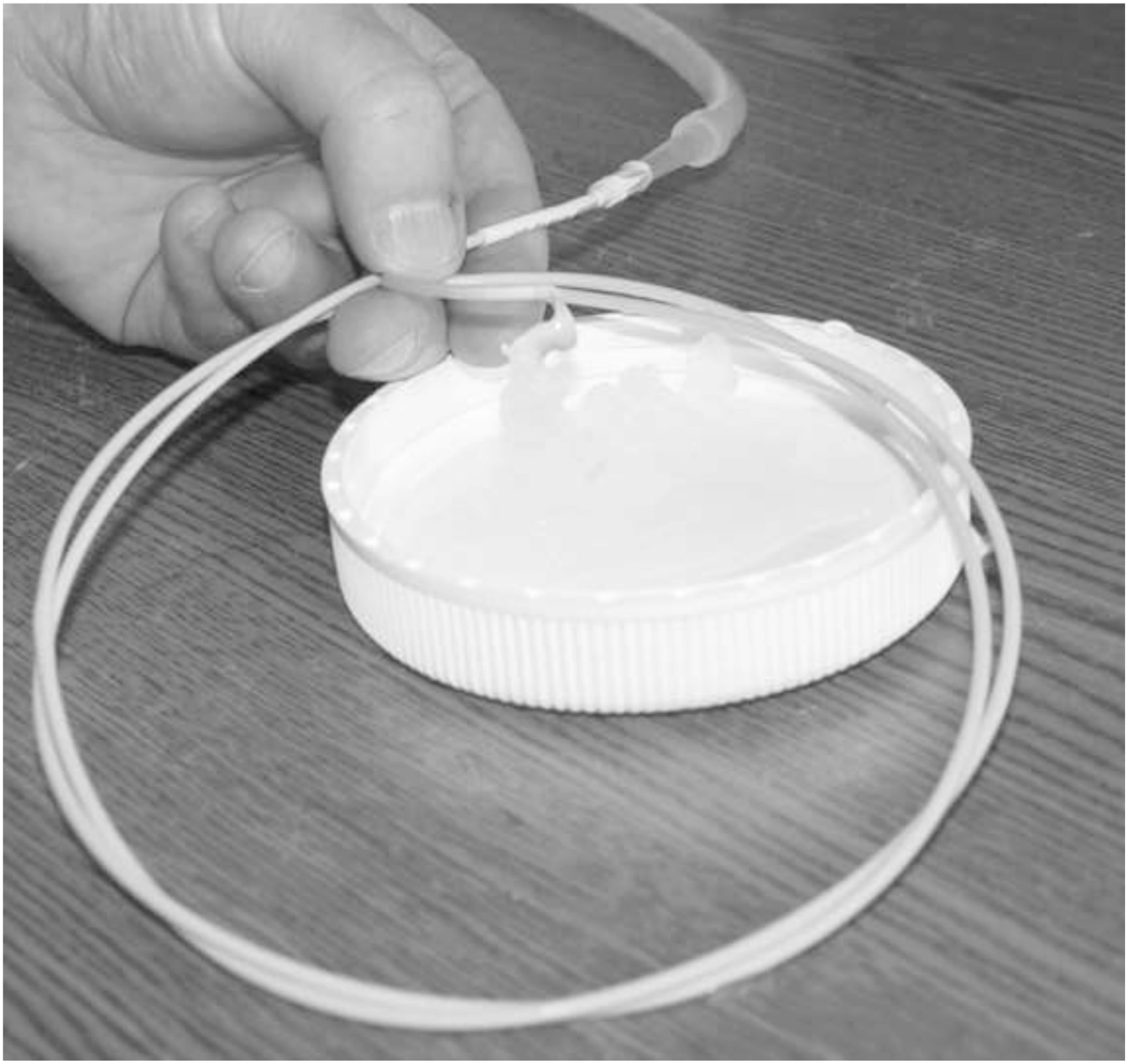


Figure 16.
Ice slurry delivery through a 100 cm long cardiac catheter.