DEVELOPMENT OF ICE SLURRY PHASE-CHANGE COOLANTS FOR INDUSTRIAL AND MEDICAL APPLICATIONS

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Abstract

Over the last 15 years, interest in using phase-change ice slurry coolants has grown significantly. Because of the high energy content of ice slurry, which is due to the phase change (melting) of the ice particles under a cooling load, the cooling capacity of ice slurry is many times greater than that of single phase fluids. Research is focused on understanding ice slurry behavior and developing highly-loaded, storable, and pumpable ice slurry coolants. Research has shown that the ice slurry must be engineered to have the correct ice particle characteristics (globular and smooth) so that it can be stored in a tank without agglomeration and is extractable for pumping through pipes at very high ice particle loading without plugging. Potential ice slurry cooling applications range from HVAC and food preservation to recent uses involving inducement of medical protective cooling. This paper provides an overview of the research and development related to the first and last ice slurry applications.

1. INTRODUCTION

Interest in using phase-change ice slurry coolants has grown significantly (Kasza and Chen, 1985, 1987). The applications range from HVAC and food preservation to most recently ice slurry being used to induce medical targeted protective cooling. This paper provides an overview of the research and development related to the first and last applications. Much effort has centered on the development of highly loaded, storable, and pumpable ice slurry and on the development of methods for making ice slurry that has these engineering attributes. Ice slurry was originally primarily envisioned for industrial applications (Kasza et al.,1988; Kasza, 2000). Over the last 8 years efforts are underway to developed special slurries and delivery methods for medical applications where inducing targeted cell protective cooling (hypothermia) is beneficial. Because of the high energy content of ice slurries, which is due to the phase change (melting) of the ice particles under a cooling load, the cooling capacity of ice slurry is many times greater than that of single phase fluids.

For the majority of past ice based cooling systems using storage, the ice slurry was not pumped out of the tank only chilled water was piped to loads. The ice slurry is melted in the storage tank. The ability to store the ice slurry without agglomeration or particle entanglement and then pump it out of a tank as ice slurry is very important to the implementation of ice slurry cooling technology (Kasza et al., 1986, 1987; Kasza and Choi, 1987). In some applications ice slurry can be made during non demand periods and be stored for later use. Both the storage and the pumped transmission of ice slurry to cooling loads has the advantage of allowing significant reductions in the size of tanks, pumps, piping, and chillers. Depending on the ice packing 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. The reliable pumping of ice slurry at high loading both out of a tank and without plugging a distribution system has only recently became feasible. Argonne 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. The use of ice slurry has the potential for greatly improving the effectiveness of District Energy Systems and for protectively cooling patients experiencing medical emergencies such as cardiac arrest or during planned surgeries.

2. PHASE CHANGE ICE SLURRY

Argonne has shown that ice slurry must be engineered at the micro-scale to have the correct ice particle characteristics (Kasza and Hayashi, 2001). In general ice particles produced and suspended in pure water produce ice slurry having poor fluidity as commonly experienced by anyone trying to enjoy an ice slush drink by sucking on a straw; the ice remains in the cup. The microscope system shown in Figure 1 has been used to study ice particle shapes and surface roughness for ice slurry with good and bad handling

characteristics. Figure 2(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 2(a) show two types of ice particles which make bad ice slurry: denderitic 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 2(b) using methods developed by Argonne 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 (see insert) 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 shaped; 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 and 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 requirement for using 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 for greatly improving the effectiveness of distributed-load cooling systems and is also being developed for medical applications.

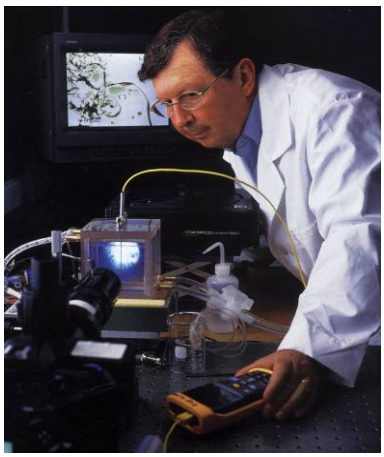


Figure 1. Microscope and cold-cell used to study micro-scale features of ice slurry particles

Figure 2. Chemical and thermal smoothing of globular and dendritic ice particles yields dramatic improvements in ice slurry behavior: (a) no smoothing; bad ice slurry; (b) with smoothing; good ice slurry

The strong influence that chemical smoothing of individual ice particle surface roughness has on the engineering mixing characteristics of an ice slurry is demonstrated through the use of the simple bench-scale apparatus shown in Figure 3. The apparatus consists of a 4 liter beaker sitting on a variable speed magnetic drive mixer platform. Testing involved filling the beaker each time with 3 liters of ice slurry having varying ice loadings from 5 to 35 % by wgt 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 4 (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 by smoothing the surface roughness on individual ice particles reduces particle entanglement and allows particles at the higher loadings to slip by each other which greatly reduces 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 with out plugging. Section 3 discusses how the improved handling characteristic of properly produced ice slurry can be used to improve the performance of building HVAC systems.

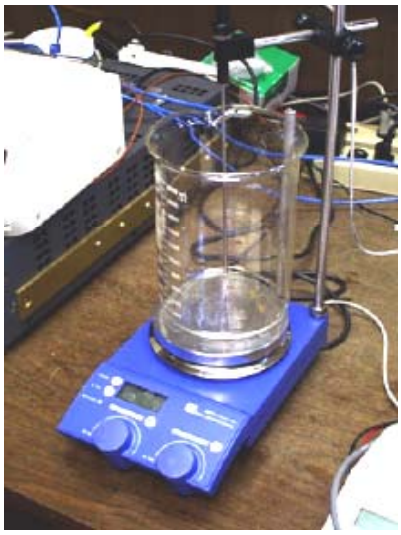


Figure 3. Bench-scale apparatus for evaluating ice slurry fluidity and mixing characteristics

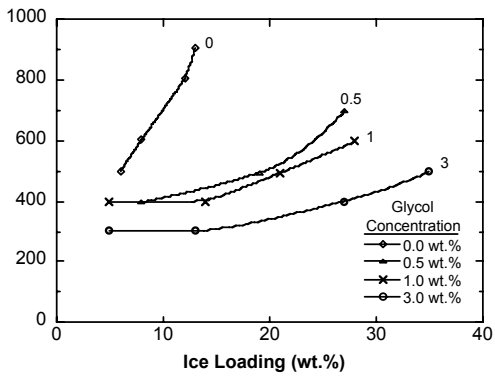


Figure 4. Chemical smoothing and mixer rpm required for mixing crushed ice particle slurry

The most important issue relating to implementation of ice slurry cooling technology 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 and sudden bulk nucleation of ice crystals*
- Freezing point depressants in aqueous binary solution and scraped or moveable cold surfaces to facilitate removal of ice crystals *
- Vacuum triple point *
- Ice Harvester with ice chunk crusher/shaver/cutter
- Direct freeze process (spraying of water into cold gas or other fluid medium)

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

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 4, ice slurry is

made using ice particle smoothing yielding ice slurry which can be pumped at > 50 % ice loadings through tubes smaller than 1mm in diameter.

3. ICE SLURRY BUILDING COOLING

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 escalating energy costs. 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. Facilities 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. Much of the foundational ice slurry coolant research for building applications was conducted by Argonne for the USA DOE. 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 (335 kJ/kg). However being able to produce ice slurry with ice loadings 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. This Section describes in more detail many of the preceding potential benefits and supporting testing.

3.1. Estimates of Ice Slurry Use Benefits

The ability to store ice slurry without agglomeration or particle entanglement during storage and pump it out of the tank as ice slurry 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). For the majority of past ice-based cooling systems using ice storage, the ice is not pumped out of the tank only chilled water is piped to loads. The ice slurry or ice chunks are 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 5 (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 flowrate can also be reduced significantly compared to chilled water. As shown in Figure 6, a new pipe system designed for the distribution of ice slurry can be reduced significantly in size over that required for chilled water delivery of the same cooling capacity.

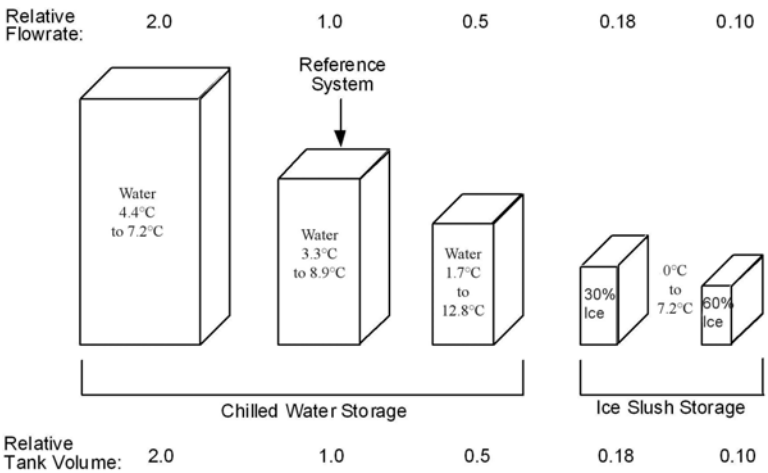


Figure 5. Comparison of coolant flow rate and storage tank volume for ice slurry and conventional chilled water

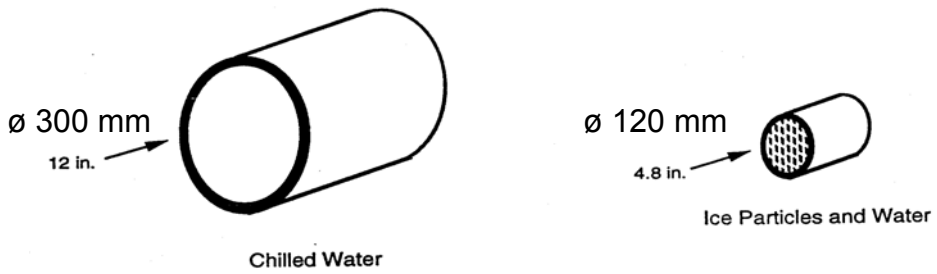


Figure 6. Using ice slurry as a coolant instead of single phase water can significantly reduce pipe size required to satisfy a cooling load

The following list summarizes the benefits of using ice slurry over single phase coolants such as chilled water for building cooling:

- Greatly increases delivered cooling capacity over chilled water and other single phase coolants
- Reduces equipment size, including chillers, storage tanks, and piping
- Ice slurry storage facilitates use of cooling load management (making ice slurry during periods of off-peak demand) and also reduces cost of storage systems
- Reduces equipment costs by reducing chiller, storage tank (by 1/10), and pipe sizes (40-60 %)
- Reduces coolant flow rates and associated flow noise
- In a retrofit situation can increase system cooling capacity without upgrading piping and storage tank sizes

3.2. Experimental Studies

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, 2001). It is desirable to store the ice slurry at the highest ice loading possible, in order to most effectively reduce tank size. Even if the ice slurry does not agglomerate in the tank, it may need to be diluted to an ice loading which is compatible with pumping it through a pipe delivery network. Argonne has made significant progress in addressing these engineering design issues in studies conducted in its Ice Slurry Facility.

Figures 7 shows a schematic of the facility used to explore ice slurry production methods involving chemical and thermal smoothing of the ice slurry during production, storage, extraction, and distribution through piping. Figure 8 shows a photo of the facility. The tanks shown are ~ 4,000 liters each and the piping is as large as 7 cm diameter.

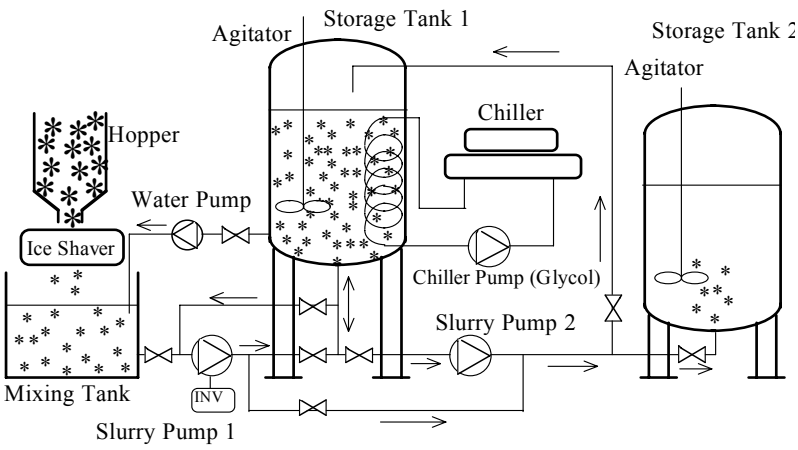


Figure 7. Schematic Argonne ice slurry facility

Figure 8. Argonne ice slurry facility

The size of the ice particles, their shape/smoothness, and loading 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 9-10 (Liu et al., 1988; Choi et al.,1988), ice slurry if correctly made can be pumped with no greater penalties than 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 strongly a function of particle size and ice particle loading even for high quality ice slurry comprised of globular smooth particles.

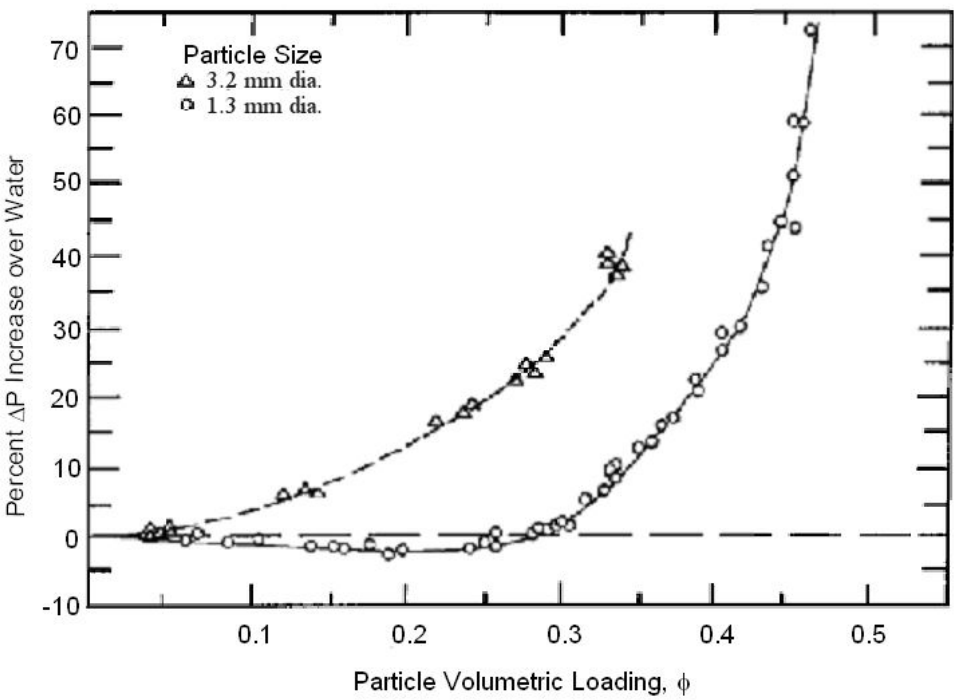


Figure 9. Influence of Particle Size and Loading on Pipe Pressure Drop (Ice Slurry Versus Water)

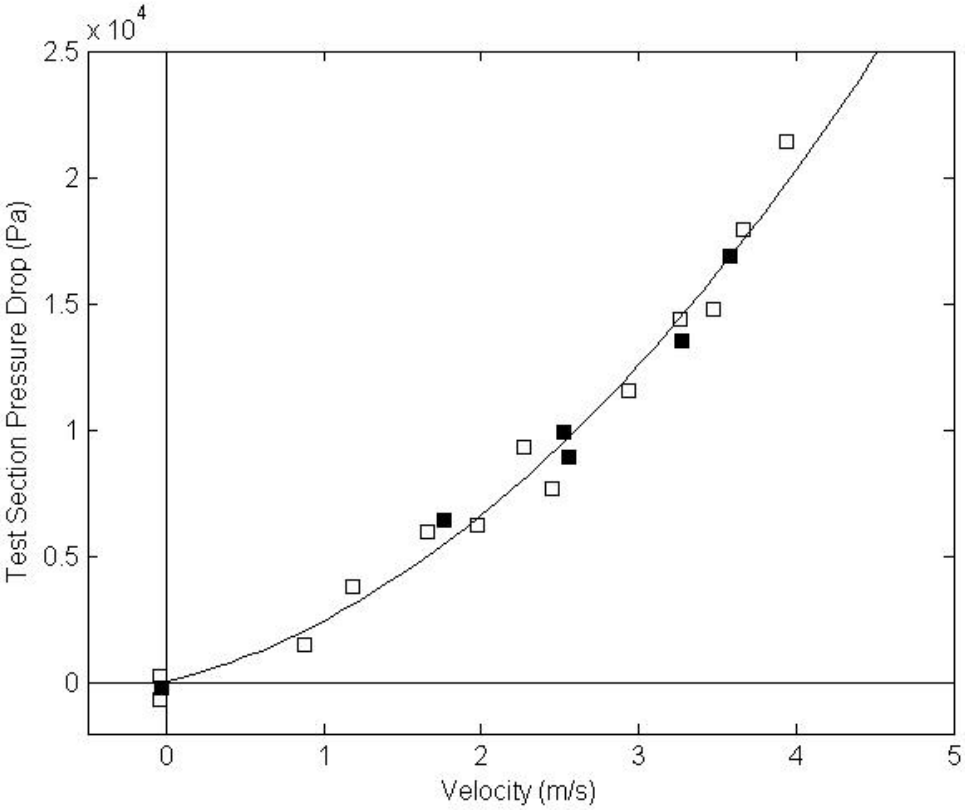


Figure 10. Pressure drop in a 7 meter long, 5 cm diameter pipe:
ice slurry (18 % ice loaded; solid symbol) and water (1°C; open symbol)

3.3. Large Scale Demonstration

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.

To this end a proposal is currently under review by the US DOE which proposes to demonstrate at Argonne the use of ice slurry for cooling multiple buildings. The demonstration if approved will be conducted by a team comprised of:

- Argonne researchers
- Argonne physical plant HVAC engineers/operators
- Industrial equipment manufactures
- Private sector energy provider firms
- HVAC consultants

The 5 year demonstration will involve supplying ice slurry cooling made in a central plant to multiple buildings on the Argonne campus. Figure 11 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.

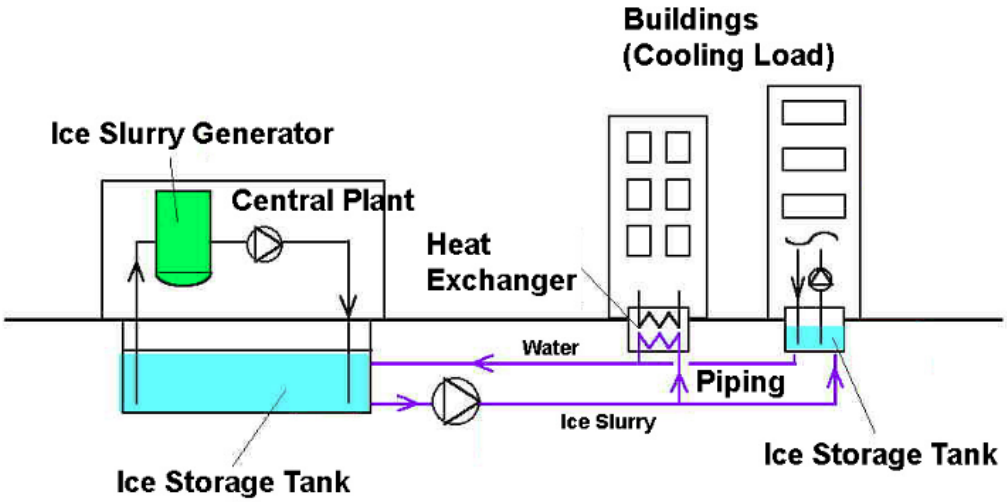


Figure 11. Schematic of distributed-load ice slurry building cooling system

The demonstration will involve a learning curve for research staff, HVAC engineers, equipment manufacturers, and facility operators. Upon successful completion, the ice slurry cooling demonstration team and the developed infrastructure will have achieved the following objectives:

- Accelerated the transfer of advanced cooling technology initially developed with DOE funding to the private sector by bringing together in a sharply focused collaborative effort: research and development groups, HVAC engineers, equipment manufacturers, energy production firms, and the end user
- Established a cooling concept which is more energy efficient and yielding operational and equipment cost reductions over current large individual systems
- Developed control and operation philosophy relative to space cooling, district cooling, and the potential for load shifting
- Established ability to optimize ice generator design and optimize ice slurry particle conditioning to achieve highly loaded storable and pumpable ice slurry
- Developed a design information data base and integrated system design approach to enable the application of ice slurry distributed cooling in a wide range of applications using components optimized for use with ice slurry coolants

4. ICE SLURRY MEDICAL COOLING

In 2000 Argonne engineers and University of Chicago (UC) Medical School doctors/researchers started developing ice slurry medical cooling under a now completed National Institutes of Health (NIH) 5yr $4 million grant. Argonne performed the ice slurry equipment research/development and collaborative animal model cooling experiments were performed at UC with UC emergency medicine doctors. The NIH grant focused primarily on developing ice slurry for inducing protective brain-heart cooling in cardiac arrest victims for the emergency response out-of-hospital environment (Becker and Kasza, 2000). Recently UC and Argonne have formed a Bioengineering Institute for Advanced Surgery and Endoscopy (BIASE). BIASE is further developing ice slurry equipment and expanding the medical uses of ice slurry cooling for inducing highly targeted protective cooling for a wide range of surgical applications. This research is also developing science-based computer modeling tools for simulating cooling. In the future these tools will be used by surgeons on a patient specific basis for planning and executing a surgery involving the use of protective ice slurry cooling.

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. Multiple tissue sites and organ systems that require complex operative manipulations to cure disease are often exposed to ischemic, traumatic, and zenobiotic insults that result in loss of function and

life-threatening infection. Ice slurry cooling is believed to be protective if the ice slurry can be produced reliably and administered easily for inducement of rapid targeted cooling.

4.1. Why Ice Slurry 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 °C, (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 °C/min) 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 (Vanden Hoek and Kasza, 2004), 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 by the equipment shown in Figure 12 using a carefully controlled production process to achieve maximum ice loading and trouble free operation. 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 the equipment has been used to make ice slurry from a commercially available blood substitute called Hextend which is produced by Hospira under license from BioTime. Ice slurry made with commercial blood substitutes allows protective cooling as well as cell nourishment to be introduced simultaneously.

Figure 12. Equipment used to produce and deliver medical ice slurry coolants

4.2. Ice Slurry Cooling Applications Being Developed

Currently five ice slurry protective medical cooling applications, described below, are being developed. All cooling applications in varying degrees contain the following components:

- further improving ice slurry production equipment and ice slurry handling characteristics,
- conducting animal model experiments to demonstrate effective ice slurry cooling and medical protection efficacy across various tissues and organs,
- conducting basic tissue and cell studies relating to improving understanding of how cooling triggers good as well as possibly negative responses during targeted cooling, and
- developing science-base computer models/simulation tools for predicting organ/tissue/blood cooling

The development of science-based simulation tools involves developing and validating 3-D computer model tools for simulating the cooling of various organs during surgery which includes development of high resolution efficient 3-D computational grid generation schemes from high resolution medical images of organs.

Initial predictions of kidney ice slurry cooling during laparoscopic surgery have been made using an Argonne developed 3-D model of kidney cooling which simulates tissue heat conduction, metabolism, and perfusion (Kasza et al., 2006). The development of more complex simulation tools for predicting heart cooling as well as interactions between multiple organs and software for patient data management are underway. The simulation tools will in the future facilitate the planning of the best surgical procedure for ice slurry delivery to achieve protective cooling on a patient specific basis.

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 °C below the normal body temperature of 37 °C after failed defibrillation is believed to be of significant benefit.

The first medical cooling application explored by Argonne and UC was for out-of-hospital emergencies resulting from cardiac arrest. As shown in Figure 13 treating cardiac arrest in the future would involve ice slurry delivery to the lungs by paramedics who would also perform chest compressions to establish some blood flow. The ice slurry delivered to the lungs without ever coming in contact with the blood, 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 therapeutic cooling (hypothermia). Upon ice slurry melting, the residual saline solution is removed by a suction tube.

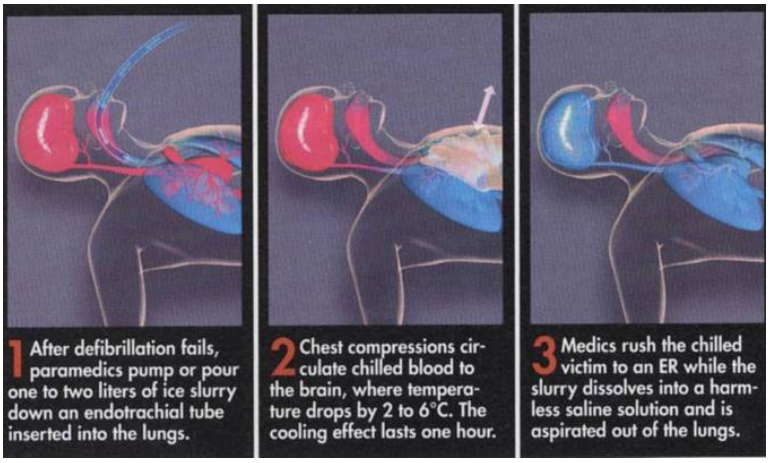


Figure 13. Cardiac Arrest: brain cooling via lungs (from Popular Science Magazine 2003)

Experiments conducted at UC using an animal model of cardiac arrest on large swine (50 kg) as shown in Figures 14-15 showed that ice slurry coolant effectively decreased the temperature of the brain and heart by 4-6 ºC in 15 minutes which is protective.

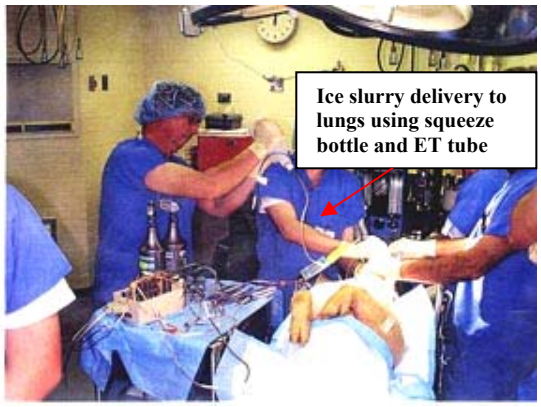


Figure 14. Cardiac Arrest: ice slurry protective cooling

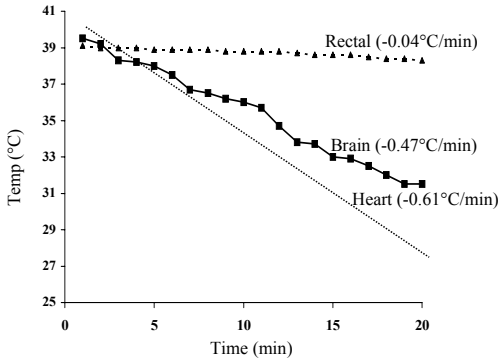


Figure 15. Cardiac Arrest: temp. for 20 min

Minimally Invasive Laparoscopic Kidney Surgery Protective Cooling

Conventional open-cavity kidney surgery involves a long incision made in the abdomen. In order to control the amount of blood lost during the surgery the renal artery and vein as shown in Figure 16 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).

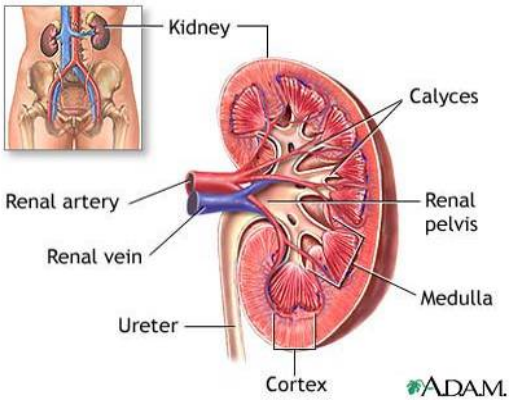


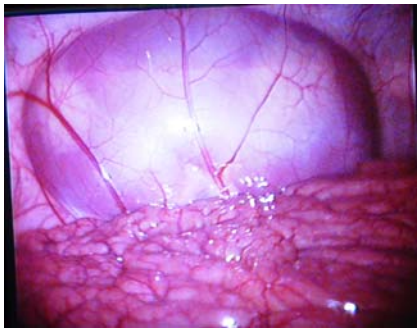
Figure 16. View of kidney

Figure 17. Laparoscopic surgery entry ports for surgical tools and ice slurry delivery tube

Laparoscopic surgery replaces the long abdominal incision in open-cavity surgery with three to four small incisions through which small ports are inserted; two ports are shown in Figure 17. These ports allow instruments to be inserted: one of which is a fiber optic endoscope/light source for viewing the patient's organs and surgical manipulations on a video monitor as shown in Figure 18. The other ports are used for the access of surgical tools such as clamping, cutting, suturing, and now for supplying pumpable ice slurry for cooling. As shown in Figure 19, ice slurry cooling involves using an engineered delivery tube inserted in a laparoscopic port for delivering and coating the outer surface of the kidney.

As shown in Figure 20, after the renal artery and vein are clamped, the kidney is then cooled to below 15 ºC and the surgery begins. Animal model data shows the kidney is protected from ischemia damage for > 90 min which significantly extends available surgery time. After the surgery has been completed, the kidney warms quickly after unclamping and the melted ice slurry is removed through a suction tube.

Figure 18. Large swine undergoing laparoscopic kidney surgery with ice slurry protective cooling



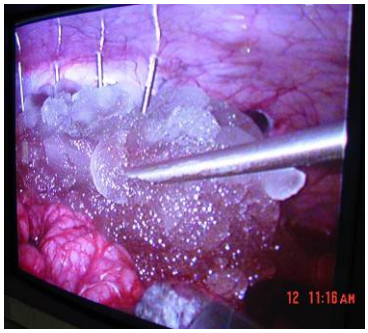


Figure 19. Endoscope view of kidney being covered with ice slurry: protects kidney for > 90 min

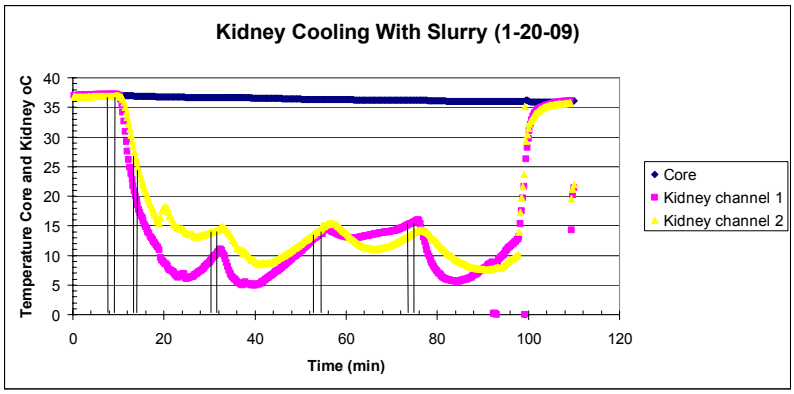


Figure 20. Temperature of kidney cooled with ice slurry for protection during 90 minute surgery

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 exploring development of improved cooling procedures and associated equipment for inducing heart muscle protective cooling. One heart cooling application being developed shown in Figure 21 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 22 shows a double-lumen catheter that has been developed to both cool the heart with ice slurry and perform a surgical manipulation.

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 ml/min 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.

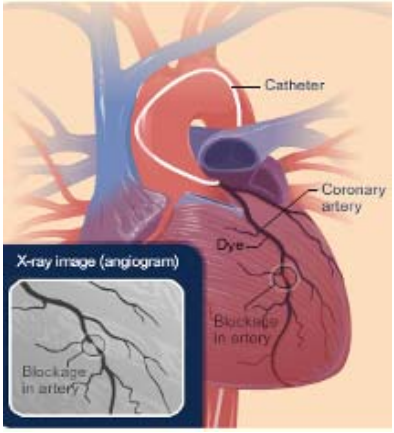


Figure 21. Schematic of heart showing catheter routed to open a blocked artery

Figure 22. Double lumen catheter for ice slurry delivery and additional surgical manipulation tools

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.

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.

5. OUTLOOK

With improving understanding of how the micro-scale features of the ice particles comprising an ice slurry influence the engineering macro-scale behavior 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 and 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 regarding avoiding ice slurry agglomeration, distribution system plugging, and minimizing pumping power requirements. Additionally and very important, careful attention must be paid to choosing the best ice source for making an ice slurry to ensure the ice slurry is suitable for a given application.

REFERENCES

1. Becker L, Kasza K, Jayakar D, et al. 2000, Rapid Induction of Hypothermia Using Phase Change Ice Slurry: Targeted Cooling of the Heart and Brain During Cardiac Arrest, presented *American Heart Association*, New Orleans, Louisiana.
2. Choi U, Liu K, Kasza K. March 19, 1988, Pressure Drop and Heat Transfer in Turbulent Non-Newtonian Pipe Flow of Advanced Energy Transmission Fluids, Proc. *Fourth Intl. Conf. on Advanced Science and Technology*, Chicago, IL, Illinois Institute of Technology, Chicago: 327-335.
3. Kasza K, Chen M. 1985, Improvement of the Performance of Solar Energy and Waste Heat Utilization Systems by Using Phase-Change Slurry as an Enhanced Heat-Transfer Storage Fluid, *ASME J. Solar Eng.* 107: 229-236.
4. Kasza K, Chen M. 1987, Assessment of Impact of Advanced Energy Transmission Fluids on District Heating and Cooling Systems (Phase I), *Argonne National Laboratory Report* :ANL-87-21.
5. Kasza K, Choi U, Kaminsky J. 1988, Advanced Energy Transmission Fluids for Heating and Cooling Systems, *ASHRAE Trans*. 93(Pt 2).
6. Kasza K, Hayashi K. 1999, Ice Slurry Cooling Research: Storage Tank Ice Agglomeration and Extraction, *ASHRAE Trans*. 105(Pt2):260-266.
7. Kasza K, Hayashi K. 2001, A Method For Measuring Ice Particle Slurry Agglomeration in Storage Tanks, *ASHRAE Trans*. 106(Pt1):117-123.
8. Kasza K. September 2000, Ice Slurry Cooling Technology, invited paper/presentation, *Energy 2000 Solutions Conference*, Honolulu, Hawaii.
9. Kasza K, Hayashi K. 2001, Ice Slurry Cooling Research: Effects of Microscale Ice Particle Characteristics and Freezing Point-Depressant Additives On Ice Slurry Fluidity, *ASHRAE Trans*, 107(Pt1): 346-351.
10. Kasza K, Chang F-C, Oras J, Fisher B, Shalhav A, Oriveto M, Mills R. June 21-25, 2006, Modeling Of Kidney Cooling Using Ice Slurry During Laparoscopic Surgery, *Bioengineering Conference*, Amelia Island, Florida.
11. Kasza K, Choi U, Kaminsky J. (U. S. Department of Energy), June 28-July 1, 1987, Optimal Energy Transmission Fluids for District Heating and Cooling Applications, *Annual Mtg. ASHRAE Conf*, Nashville, TN.
12. Kasza K, Choi U. June 21-25, 1987, Advanced Energy Transmission Fluids for District Heating and Cooling, *Proc. 78th Ann. Conf. of the IDHCA*, Baltimore, MD: 202-211.
13. Kasza K, Choi U, Kaminsky J. (U. S. Department of Energy), October 1986, Reducing the High Costs of District Heating and Cooling, *Specification. Eng.* 56(4): 39-42.
14. Laven B, Kasza K, Rapp D, Orvieto M, Lyon M, Oras J, Beiser D, Vanden Hoek T, Son H, Shalhav A. July 2006, A Pilot Study Of Ice-Slurry Application For Inducing Laparoscopic Renal Hypothermia, *International British Journal of Urology*.
15. Liu K, Choi U, Kasza K. 1988, Pressure Drop and Heat Transfer Characteristics of Nearly Neutrally Buoyant Particulate Slurry for Advanced Energy Transmission Fluids, *Proc. 3rd Intl. Symp. on Liquid-Solid Flows ASME*, New York, FED. 75: 107-113.
16. Otake H, Shite J, Paredes OL, Shinke T, Yoshikawa R, Tanino Y, Watanabe S, Ozawa T, tsumoto D, Ogasawara D, Yokoyama M. Jan. 16 2007, Catheter-based transcoronary myocardial hypothermia

attenuates arrhythmia and myocardial necrosis in pigs with acute myocardial infarction. *J Am Coll Cardiol*. 49(2):261-2.

17. Vanden Hoek T, Kasza K, Beiser D, Abella B, Franklin J, Oras J, Alvarado J, Anderson T, Son H, Wardrip C, Zhao D, Wang H, Becker L. 2004, Induced Hypothermia by Central Venous Infusion: Saline Ice Slurry Versus Chilled Saline, *Critical Care Medicine*, 32(9): S425-S431.