SlurryICE ™

THERMAL ENERGY STORAGE

DESIGN GUIDE

SLURRY-ICE APPLICATION GUIDE

1 - INTRODUCTION

1.1. History of Refrigeration

Jacob Perkins, an American living in London, patented the first closed vapour compression refrigeration system, receiving British Patent 6662 dated 1884. Ethylether was utilised as the refrigerant. Refrigerant grade Ammonia production began in the period 1876 to 1879 by the F.M.McMillan Company and widely used in industry, along side Sulphur dioxide and Methyl Chloride as alternatives.

In the early years of refrigeration the available refrigerants were less than satisfactory, being either flammable, toxic or both. The risks involved using the early refrigerants directly were high and therefore various secondary cooling brines so called **"Secondary Refrigerants"** are utilised to cool product and process indirectly.

In 1928, Thomas Midgley introduced a small quantity of R21 and demonstrated that it was of low acute toxicity and non-flammable refrigerant. What followed was a very methodical evaluation of a large number of chlorofluorocarbons, culminating in the dramatic introduction of **R12 (CFC)** at a meeting of the American Chemical Society in 1930. This was the beginning of the modern refrigerants as we know them today.

In 1974, S. Rowland and M. Molina developed a CFC/ozone hypothesis in which chlorofluorocarbons (CFCs), along with other gases, were accused of harming the earth's atmosphere by two phenomena described as:

The ***Greenhouse Theory,*** which states that chemicals known as "Greenhouse Gases" absorb infra-red radiation, intercepting it leaving the earth's atmosphere and resulting in climate warming.

The ***Ozone Depletion Theory***, which states that certain gases accumulating in the upper atmosphere will, through a complicated series of chemical reactions, catalyse the destruction of ozone and thus upset the balance of its continuous creation and destruction.

The severity of any potential regulations and the speed with which they are implemented can depend heavily on public pressure and the realisation of the extent of damage which was under-estimated during early studies in the mid 1970's. The latest scientific evidence forced politicians to re-consider the restrictions in of CFCs 1987 with the Montreal Protocol and later in 1992 with the Copenhagen Agreement, which shortened the phase out dates.

1.2. Alternatives

Society's reliance on vapour compression cooling technology ranges from critical medical applications, to providing a cool beverage or a child's ice cream treat on a sunny day. As a result, modern air conditioning and refrigeration technologies together with a wide range in food processing and preservations infra-structures have evolved around wide spread production of the vapour compression cycle. Furthermore, emergence of CFC and HCFC working fluids since the 1930's provided fresh impetus to already existing technology and gave rise to an ever expanding spread from the basic applications.

Figure: 1.1.1 shows current alternative refrigerants nevertheless the structure of the alternative refrigerants still remains as the eight basic elements identified by Thomas Migley's team in the early 20th century.

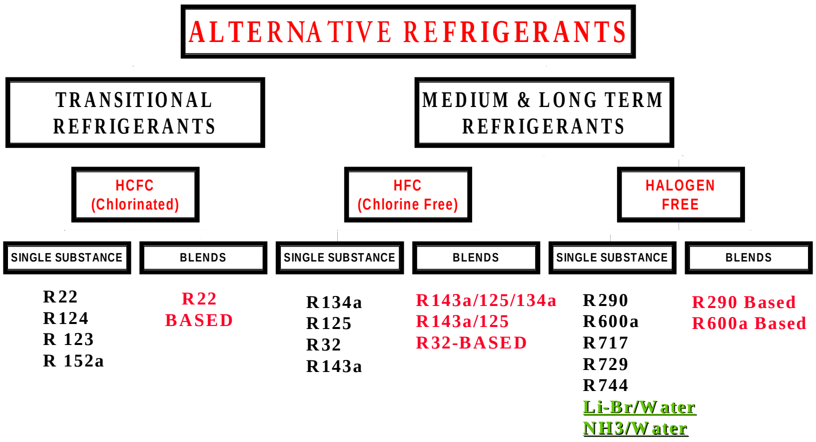


Figure 1.1.1 : Current Alternative Refrigerant Options

It is vital to establish a balance between "energy consumption" and "environment protection". Any change in refrigeration technology by means of introducing new refrigerants or by adopting new techniques must be carefully balanced to reduce the overall environmental impact. Therefore a method of calculation **(TEWI)** has been developed in which the influence upon the Greenhouse Effect (Global Warming Impact) can be judged for the operation of individual refrigeration plants.
Direct or indirect ice usages has also expanded over the years to reduce operational costs and improve system control. Dynamic or Static ice production methods have been developed for various applications.

Environmental concerns over the ozone depletion potential of some CFCs used today have prompted a search for alternative cooling technologies. Slurry ice has the potential to achieve considerable environmental as well as economic benefits for both central cooling systems and direct ice production for ever expanding ice applications. Any of the alternative primary refrigerants can be used for slurry ice production, The cooling capacity of slurry ice can be four to six times higher than that of conventional chilled water, depending on the ice fraction . The nature of the Binary (Crystal) ice formation allows end users to pump the ice, providing easy handling and intimate contact with the product, for higher chilling efficiencies.

There are many slurry ice-based cooling systems operating around the world. Most air conditioning installations are based on ice storage, where the warm return water is used to melt the ice when required. Slurry ice is also circulated in close loop distribution systems directly for process and product chilling applications. Some of the commonly used applications are as follows;

INDUSTRIAL APPLICATIONS

Ice Storage
Process Indirect Cooling
Process Direct Cooling
Quick Chilling/Freezing
Cold Immersion Baths
Batch Cooling
Process Machinery Cooling

COMMERCIAL APPLICATIONS

Ice Storage
Supermarket Refrigeration/Air Conditioning
Fast Cooling of Food Product Directly (Fish, Meat, Vegetable)
Fast Cooling of Food Product Indirectly (Milk, Beer, Oil)
Display of Food Product

SPECIAL APPLICATIONS

Marine
Mine Cooling
District Cooling Systems

This manual describes the advantages and disadvantages of using slurry ice cooling systems. The most important physical properties and behaviour of ice slurries are presented in a form that will help practising engineers and consultants to develop effective and efficient Slurry-Ice based cooling system designs.

2.0 CURRENT ICE PRODUCTION TECHNOLOGIES

Ice production techniques can be divided into two main groups namely ***Dynamic*** and ***Static*** systems. and the produced ice can be used either ***directly*** or ***indirectly*** to chill the product or system. The direct usage generally remains within the food sector to chill products such as fish, vegetables, meat, poultry etc. and indirect usage generally utilised for the latent heat cooling effect for process cooling such as ice storage, TES systems for air conditioning and process cooling as secondary cooling medium.

2.1 - Static Ice Production Systems

This technique is probably the oldest in use. In principle, the ice formation and melting takes place without any physical removal of the ice . The most common used techniques are as follows;
Ice Builder : Two type of commercially available techniques have been widely used in HVAC industry namely ice builders and ice banks

-Ice on Coil
Refrigerant or Glycol water solution at a temperature of between -4°C and -10°C is circulated within a serpentine coil, which is submerged in an insulated tank of water in order to form ice on it. The ice builder tank consist of a low pressure air pump or paddle blade to agitate the system in order to achieve even distribution of ice melting and formation. The thickness of ice is measured by a sensor to control the operation and the relevant details can be seen in Figure:2.1.1.

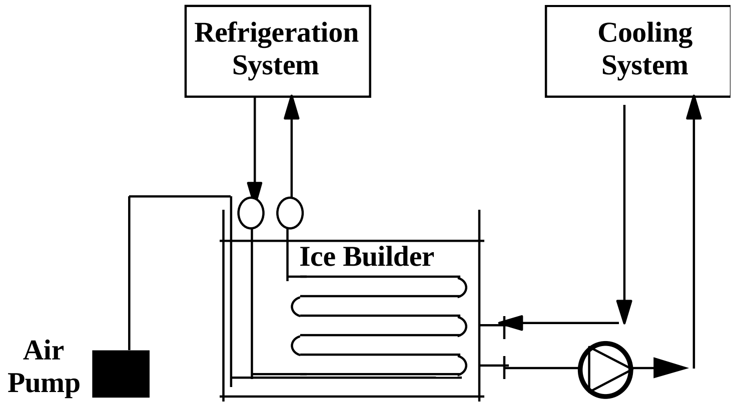


Figure 2.1.1 : Ice Builder Concept

Ice Banks:
The ice bank consists of a pressurised, closely packed polyethylene tube heat exchanger. Low temperature glycol solution is circulated through the tubes, which freezes the water around them. The water in the insulated tank is almost frozen solid at the end of the charging cycle. The control of the system can be provided by the ice level sensor in the tank. The system water is circulated through the tube tank for both techniques, to satisfy the cooling demand. A typical Ice Bank system can be seen in Figure:2.1.2.

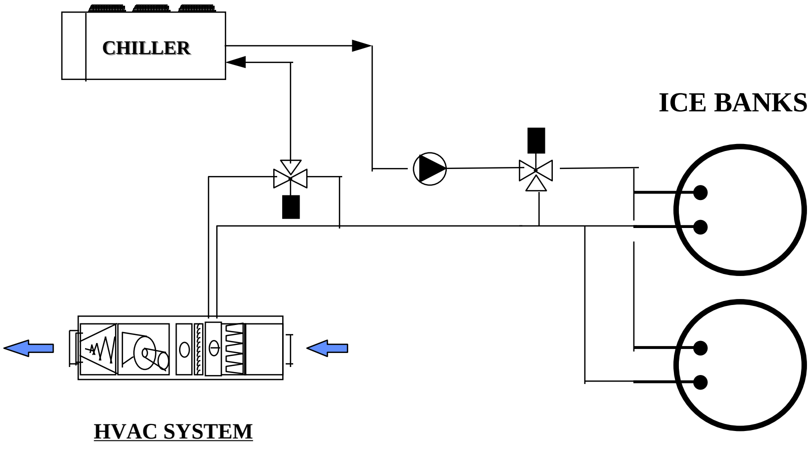


Figure 13 : Ice Bank Systems

Encapsulated Ice Storage:

The basic principle of this technique is the sealing of water or **P**hase **C**hange **M**aterial (PCM) in capsules which are positioned in an insulated tank and the circulation of process fluid around the capsules Figure 2.1.3. at below freezing point during charging and vice versa normally with flow reversal for the discharge mode.

Capsules can be in any shape but the most commercially used shapes are Balls or Flat containers. The charging and discharging cycle can be controlled by water levels in an inventory tank which is subject to level change due to ice expansion and contraction during the freezing and melting process respectively or by process fluid temperatures.

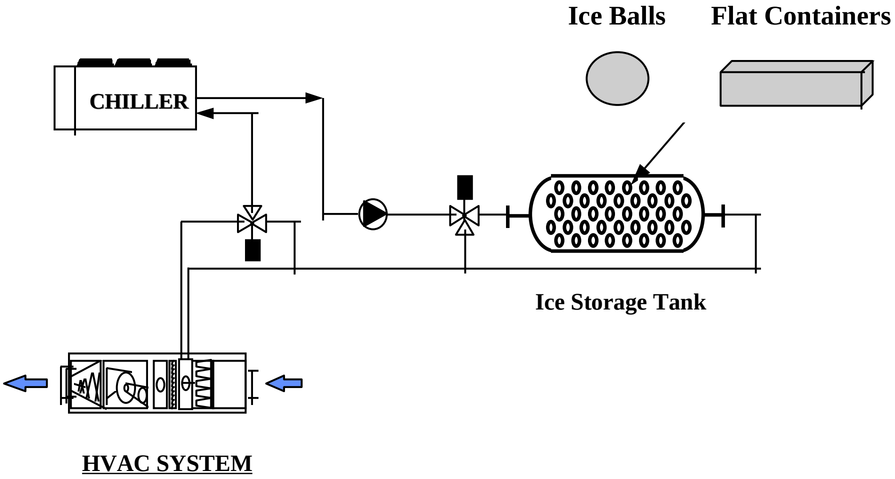


Figure 2.1.3 : Encapsulated Container Concept

2.2 - Dynamic Ice Production Systems

Ice is periodically harvested from the freezing apparatus to a storage bin and the stored energy is recovered by circulation of water through ice in the bin to supply the chilled water system during normal operation. There are many commercially available systems in the market and the most common used systems are as follows;

Ice Harvester:

Ice is built on a vertical surface which is the evaporator section of the refrigeration system. Water is circulated from the storage tank, over the plates until a certain thickness, normally in the region of 8-10 mm ice is formed. This freezing process takes approximately 20 minutes .The ice is harvested by means of hot-gas by-pass from the delivery port to the evaporator plates to warm the surface to about 5 Deg C, resulting in the ice in contact with the plates melting and falling into a sump or ice tank, to which chilled water from the system is circulated. The general layout of a ice harvester system can be seen in Figure: 2.2.1.

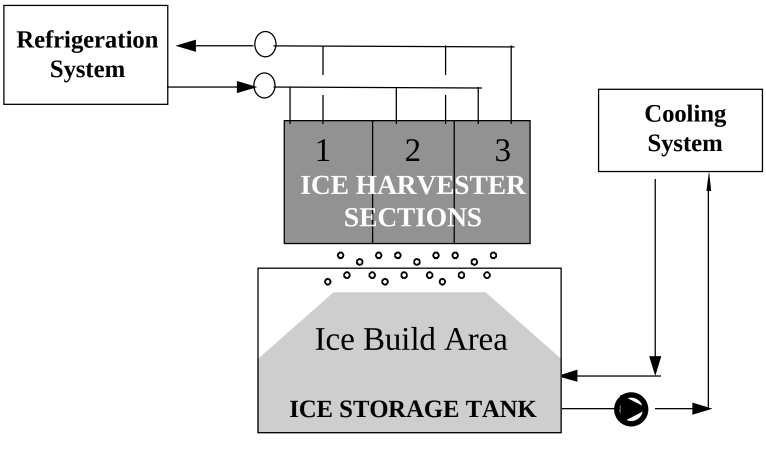


Figure 2.2.1 : Ice Harvester

Tubular Ice:
In principal this technique is identical to the Ice Harvester system, the only difference being that the ice is produced within a tube rather than on the surface of plates. The storage and system applications are identical to the ice harvester techniques.

Ice Flakes:
A revolving freezing apparatus produces ice flakes continuously and the flake ice is collected at the bottom drum of the machine for later use by means of circulating chilled water through the ice tank to satisfy the cooling demand.

Slurry Ice:
In this system a binary solution is cooled below its freezing temperature within a Falling Film, scraper, vacuum or supercooling heat exchangers. The refrigerant which is circulated outside the tube supercools the binary solution into millions of fine crystals which are then pumped into a storage tank for later use, or directly to satisfy the process load. During the cooling mode, warm solution is circulated through the storage tank where it is cooled by the crystallised solution and then pumped directly to satisfy the air conditioning chilled water circuit.

3 - SLURRY ICE TECHNOLOGY

Slurry-ICE is a suspension of a crystallised water-based ice solution and the icy slurry can be pumped, hence, it is also called ***" Liquid-ICE"*** or ***"Pumpable-ICE".*** It also as potential use as a secondary cooling medium, directly on product or alternatively for thermal energy storage, whilst remaining fluid enough to pump.

Slurry-Ice is a very versatile cooling medium. The handling characteristics, as well as the cooling capacities can be matched to suit any application by means of simply adjusting the percentage of ice concentration. At 20-25% ice concentration, **Slurry-Ice** flows like conventional chilled water while providing 5 times the cooling capacity. At 40-50% ice concentration, it demonstrates thick slurry characteristics and at 65-75% ratio, **Slurry-Ice** has the consistency of soft ice cream. When **Slurry-Ice** is produced in dry form, (i.e. 100% ice), it takes the form of non-stick pouring ice crystals which can be directly used whatever the product and process.

Slurry-Ice has the potential for use as a secondary cooling medium directly or alternatively for thermal energy storage, while remaining fluid enough to pump.

The **Slurry-Ice** system is a *"Dynamic Type"* ice storage system which offers the pumpable characteristic advantage over any other type of dynamic systems. Compact equipment design and the pumpable characteristics offers tremendous flexibility for the location of the storage tank(s) and the most economical capacity and duty balancing for any given application. The storage tank can be placed under, beside, inside, or on top of a building and can be in any shape and size to match the building and architectural requirements. Multiple small storage tanks can be used instead of a single large *"Static Type"* ice storage tank.

Slurry-Ice does not suffer from the *"Static Type"* disadvantages of ice bridging and ice insulation effects. As it comprises microscopic ice crystals , a total surface area for heat exchanging is very large in comparison with the conventional ice builder concept and therefore ice instantly melts to meet varying cooling load. Hence, ensuring steady and accurate system leaving temperature control.

Slurry-Ice offers superior performance over the conventional flake and block ice systems as a chilling medium.

Slurry-Ice does not only offers higher efficiency and cost effective ice production but also unique pumping and easy handling characteristics provide totally sealed "Hygienic Systems", increased production, flexibility of operating temperature and consistency of application, for optimum results.

Direct contact **Slurry-Ice** chills faster, providing instant protection, maintaining freshness and preserving colour. The tightly packed ice formation inhibits air circulation which causes premature ice melting of solid ice for transport and storage applications. Hence, **Slurry-Ice** lasts longer.

3.1 Generator Types

For the design of an slurry ice production techniques, there are presently a number of commercially available slurry ice production systems to choose from.

3.1.1 Supercooled Slurry Ice Production;

The "*Supercooling Concept*" has an evaporator which operates on the principle of water supercooling. A stream of water, when cooled slowly, can be supercooled by several degrees below normal freezing point without ice forming on the wall. Before leaving the evaporator, the supercooled water, flow is physically disturbed in order to generate ice crystals. The ice fraction depends on the supercooling of the liquid leaving the evaporator and increases by approximately 1.25% / ^{0}C supercooling.

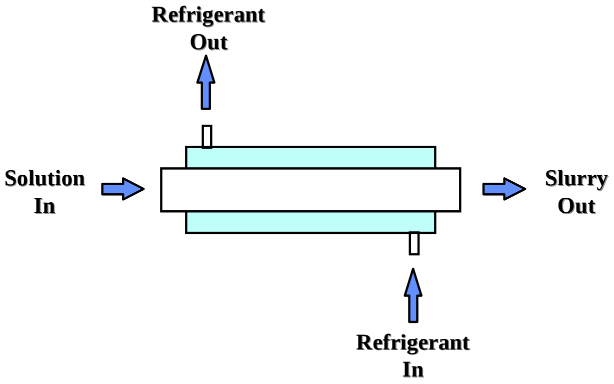


Figure 3.1.1. Supercooled Slurry Ice Generator

3.1.2. Scraper Type Systems

Scraper type slurry ice generators produce ice in a brine solution at various temperature ranges, depending on the solution concentration. The freeze point depressant and the mechanical scraper prevent ice formulation on the evaporator wall.

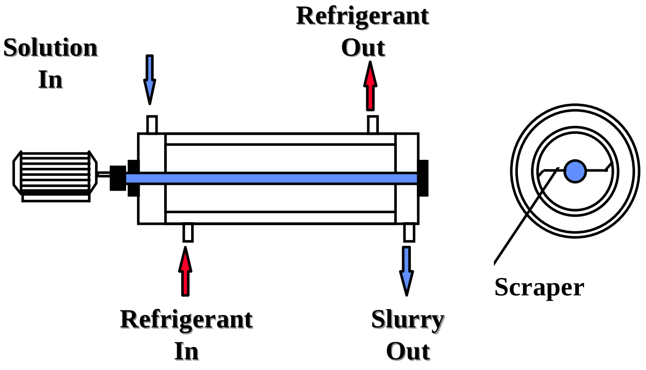


Figure 3.1.2. Scraper Type Slurry Generator

Scraper type evaporator accepts either water (brine) solution or slurry ice. As the liquid is cooled, ice crystals are formed in the bulk of the liquid. An agitator system is used to move the cold water from the vicinity of the wall to the bulk of the liquid. The increase in ice fraction for each pass depends on the mass flow rate through the chiller.

3.1.3 Ejector System

The ejector system relies on heat exchange between two dissimilar fluids. A non-miscible fluid which is heavier than water, is cooled below water freezing temperature via a conventional secondary refrigeration chiller. The fluid then passes through an ejector system in which the high pressure of the fluid is used to draw water from the tank circuit. The nature of the ejector system creates sufficient turbulence and cooling effect to turn ordinary water to ice crystals. Once the mixture reaches the settling tank, the lighter ice crystals float to the top of the tank and the heavier heat transfer fluid settles at the bottom of the tank for recirculation.

The settling tank requires careful design in order not to disturb heat transfer fluid, water and ice levels. Furthermore, as the ice floats to the top of the tank, it presents difficulty in maintaining steady ice concentration levels for the supply line.

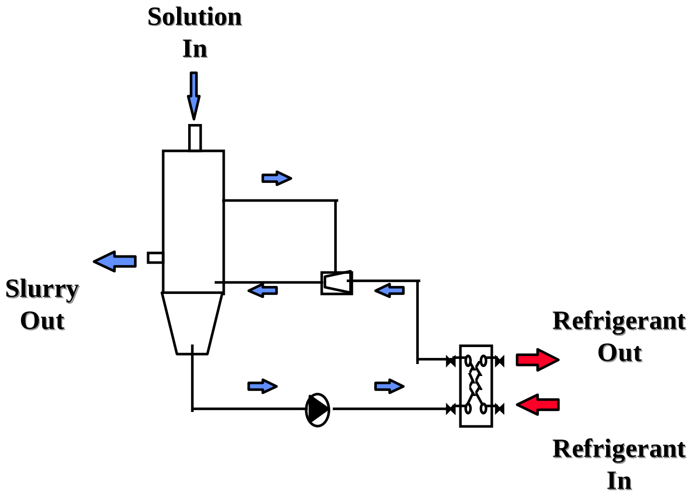


Figure 3.1.3 Ejector Type Slurry Ice Generator

3.1.4. Vacuum Type Slurry Ice Production:

The saturation temperature of water changes with the pressure (similar to absorption chiller concept) and water reaches its triple point at 0.0061 Bar, 0.01 °C. At this state, evaporative cooling is produced by extracting the latent heat of evaporation from the water. The concept can be best described as "Flash-Evaporation" which requires vapour removal by means of mechanical compression with electric motor or thermal compression with steam as the driven source. The compressed vapour later liquefied in the condenser to complete the loop. This type of slurry-ice machine operates at sub-atmospheric pressure and therefore non-condensable gases must be removed, similar to absorption refrigeration machines.

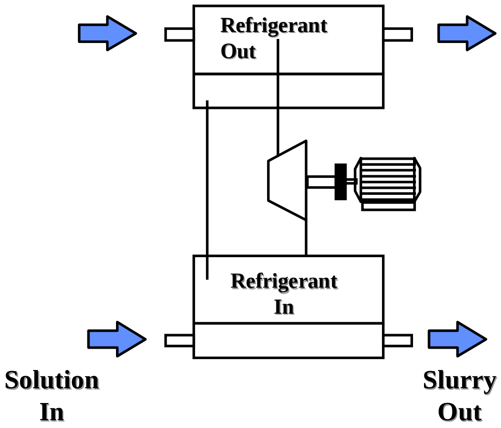


Figure 3.1.4. Vacuum Type Slurry Ice Generator

3.1.5. Falling Film Type Slurry Ice Machine;

The falling film slurry ice generator is based on conventional vertical flooded type shell and tube heat exchanger. The internal falling film process is based on supercooling the solution which is disturbed by a spinning rod in order to overcome the formation of solid ice and prevent it sticking to the inner surface of the pipe. Once the solution is supercooled and disturbed, it forms microscopic fine binary ice crystals which are collected at the bottom of the vessel for distribution. The essential ice concentration and capacity control can be adjusted by means of either individually controlling the suction pressure, solution flow rates or a combination of both.

There is no friction between the rod and the tube wall and the slurry ice solution acts like a lubricant. Therefore the energy required to drive the rod and the consequently lower maintenance requirement offer efficient, reliable and economical operation.

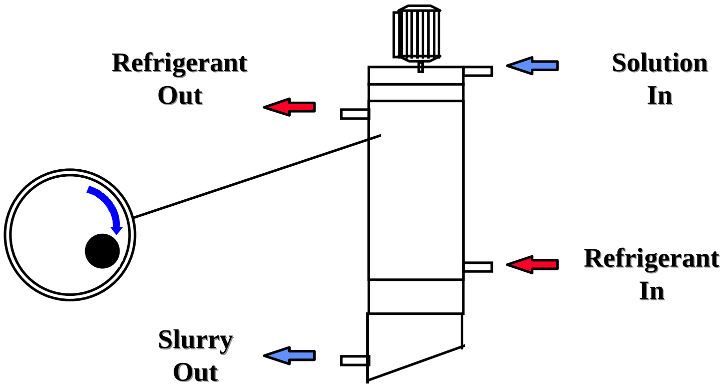


Fig 3.1.5. Falling Film Type Slurry Ice Machine

3.2 SLURRY ICE CHARACTERISTICS

The important benefit of slurry ice is the increased “cooling” capacity compared with that with conventionally chilled water systems at 6^0C. The behaviour of ice slurries and their variation with ice fraction are reviewed in this section.

3.2.1 Slurry ice Cooling Capacity

In conventional chilled water systems, the enthalpy difference of water between 6 and 12 ^{0}C results in a cooling capacity of about 30 kJ/kg. Because of this fairly low sensible heat, large volumes of water need to be pumped for a given load. The use of slurry ice significantly decreases the volumetric flow requirements.

The latent heat carried by ice particles in the water adds great cooling capacity to the flow. The additional cooling capacity of an slurry ice relative to conventional chilled water at 6 ^{0}C and water at the freezing point is shown in Figure 3.2.1. The ordinate of the graph in Figure 3.2.1 represents the factor by which the cooling capacity of water at 7^0C should be multiplied to determine the effect of the slurry ice at different ice fractions. For example, compared with chilled water with supply / return temperatures of $6/12^0$C, the cooling capacity of slurry ice operation at 0/13 °C with ice fraction of 20% equals to 144 kJ/kg (4.8 x 30 = 144).

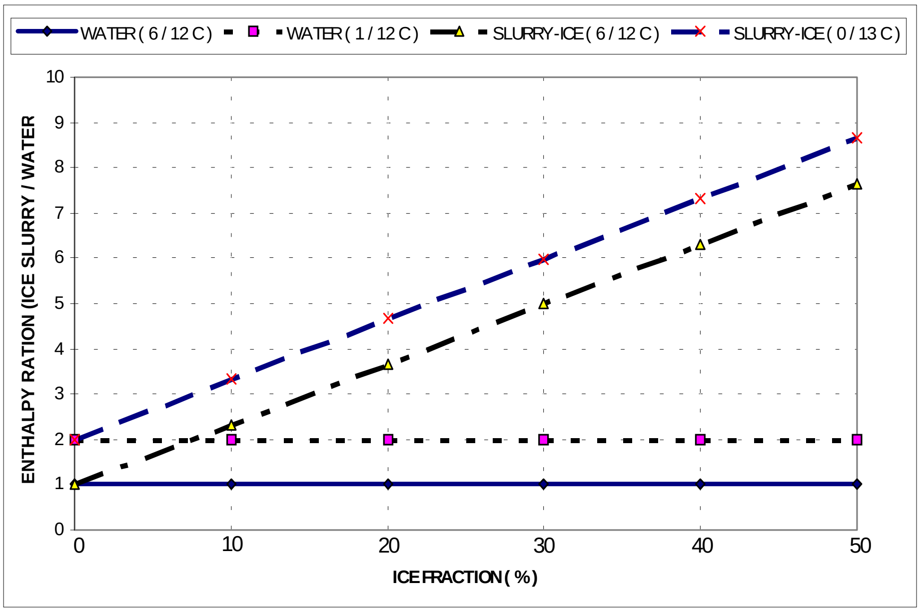


Figure 3.2.1. Latent Heat Capacity Comparison between Chilled Water and Slurry-Ice

Another way of quantifying the benefits of slurry ice over water is to compare the reduction in pipe diameter and / or pressure gradient that can be achieved with ice slurries. Figure 3.2.2 shows the

reduction ratios that can be realised as a function of ice fraction. It is clear that major pipe diameter reductions can be realised for a constant pressure gradient.

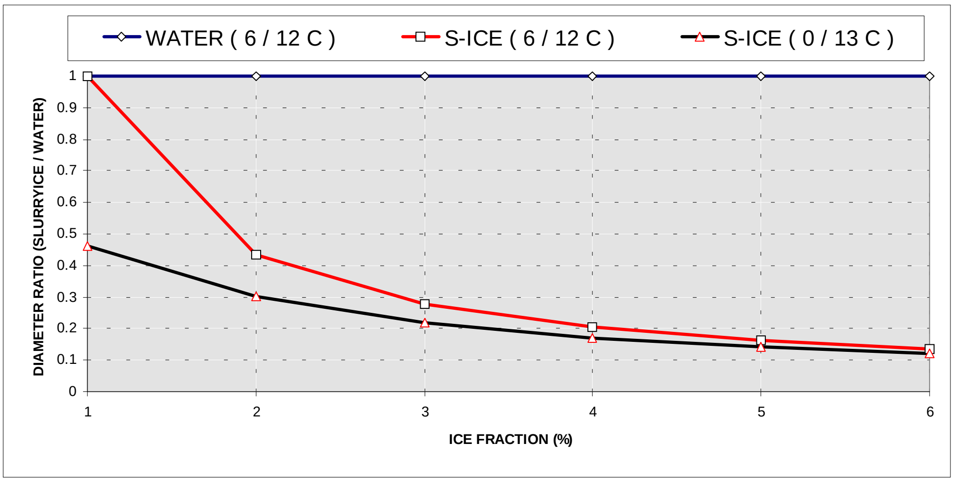


Figure 3.2.2. Pipe Diameter Reduction Comparison

3.2.2 Slurry ice Types

The shape of the ice particles in the slurry depends on the method of chiller technology used. The shape may vary between small spheres (generated in water containing freeze point depressants) to flaky crystals or coarse, pebble shaped ice particles. The physical behaviour of ice slurries, especially that relating to pressure gradient, depends on the shape of the ice particles.

3.3 Slurry ice Behaviour

3.3.1 Pipes - Variation of Pressure gradient with Ice Fraction

Pressure drop in a pipeline is a function of the friction factor (itself a function of the relative roughness of the pipe wall, and the Reynolds' number), the length-diameter ratio, the velocity and the density of the liquid or slurry. The density of an slurry ice decreases marginally with an increase in ice fraction. However, this decrease in density is not enough to make an observable difference in the pressure drop measurements. Depending on the physical shape and size of the ice particles, a number of studies indicate no change in pressure drop at low ice fractions and a marginal increase in pressure gradient at higher ice fractions. A decrease in pressure gradient is usually observed with coarse ice particles. This decrease in pressure gradient is caused by a reduction in turbulence due to the presence of ice in the water. Up to a certain ice fraction, these coarse ice particles act as a friction reducing additive.

At low velocities, the reduction of turbulence allows phase separation to occur with ice floating to the top of the channel. This will increase the pressure gradient. For a well-functioning large scale cooling system, the slurry ice would be maintained in a homogeneous state. This can be achieved by operating the distribution system above the minimum velocity, as shown below.

A minimum velocity, V_{min}, must be observed for ice fractions between 0.1 and 0.25 as highlighted in Figure 3.3.1. Below a minimum velocity, the pressure gradient increases when the velocity is decreased. Phase separation, with ice floating to the top of the pipe, causes the effective liquid flow cross-section to decrease. The slow moving or stationary ice mass at the top of the pipe effectively decreases the flow area and increases the liquid velocity.

A number of pressure drop experiments conducted at slurry ice velocities over 3m/s and ice fractions in excess of 20% in straight tubes with internal diameters of 25, 51 and 76 mm indicate that no difference in pressure gradient between water and slurry ice occurs. However, at slurry ice velocities below 1 m/s, the loop pressure drop was slightly above the pressure drop measured for water only.

In principal, friction factors in ice slurries (± 0.15 ice fraction suspensions of fairly coarse ice particles with 1.2 cm average diameter in a 10 cm diameter tube) are comparable to those for solids-free water at velocities from 1 to 1.5 m/s. Below this velocity, phase separation (flotation of the ice) may cause an increased frictional drag in the upper region of the pipe cross section, depending on the type of Binary ice solution.

This situation is similar to the pressure gradient response to other gas-solid and liquid-solid situations. The solids loading at which the pressure gradient is affected, increases with velocity. At higher velocities, the increased turbulence maintains near-homogeneous mixtures at higher solids loading.

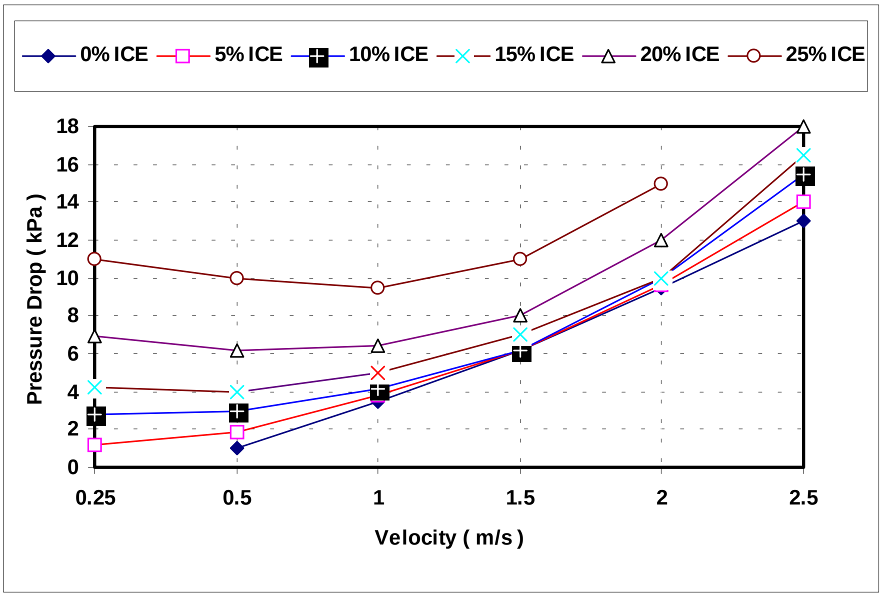


Figure 3.3.1. Slurry Ice Velocity Vs Pressure Drop Study

3.3.2 Heat Exchangers - Variation of Heat Transfer Co-efficient with Ice Fraction.

Calculations of overall heat transfer co-efficient across a plate heat exchanger for melting the slurry ice indicates that although the overall heat transfer co-efficient increases with increasing flow rate through the heat exchanger, as expected, an increasing ice fraction reduces the overall heat transfer co-efficient. At the higher mass flow rates, a 17-20% reduction in the heat transfer co-efficient can be expected when the ice fraction was increased from 0 % to 15%. The effect is illustrated for a typical plate type heat exchanger in Figure 3.3.2.

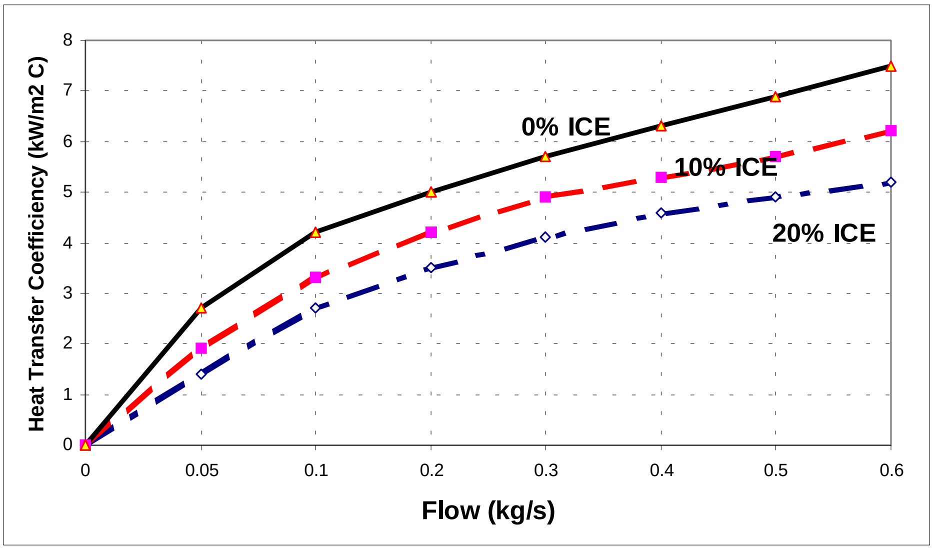


Figure 3.3.2. Flow Vs Heat Transfer Co-efficiency Study

This reduction can be explained by the fact that slurry ice reduces turbulence in the liquid. In particular, if an existing chilled water plate heat exchanger is used for slurry ice operation for an identical duty the heat transfer across the plate heat exchanger reduces due to laminar rather than turbulent flow. Although the heat transfer co-efficient is reduced in slurry ice flow, the melting ice keeps the primary liquid at or near the freezing point for a significant fraction of the heat exchanger surfaces. The increased log-mean temperature difference allows for the design of a more efficient heat exchanger.

3.3.3. Pumps

There are no problems associated with pumping ice slurries up to a certain ice fraction. This threshold ice fraction for pumping is a function of ice particle size and geometry. For small spherical ice particles (diameter < 1 mm), the ability to pump slurry ice should not be impaired at ice fraction below 0.30. At ice fractions above 0.40, slippage of the standard centrifugal pump impeller has been observed and therefore ice fractions above 0.40 may require special pump.

In principle, at ice fractions where the pressure gradient is not severely affected by the ice loading, pumping slurry ice should not cause any problems.

The change in pump characteristics between water and slurry ice at various ice fractions in viscosity form for the centrifugal pump is shown in Figure 3.3.3.1. For a constant flow, the pump head decreases slightly for an increase in slurry ice. The existing sites and laboratory test results indicate pump head decreases by about 10% from 0 to 0.25 ice fraction. In general, the designer should expect nominal changes in both flow and power consumption at varying ice fractions.

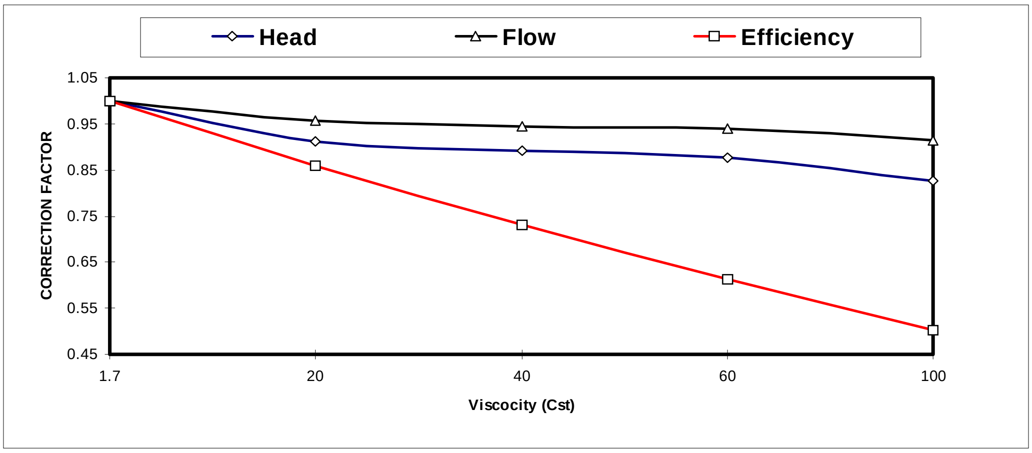


Figure 3.3.3.1 Slurry Ice Concentration Impact on Pump Operation

Furthermore, it is vital to allow sufficient pump head capability to overcome the start-up operation which requires higher pump head pressure due to lack of ice concentration i.e. reduced latent heat capacity within the solution.

A typical 100 kW duty operation and associated pump absorbed power comparison is illustrated in Figure 3.3.3.2 for various fluid options.

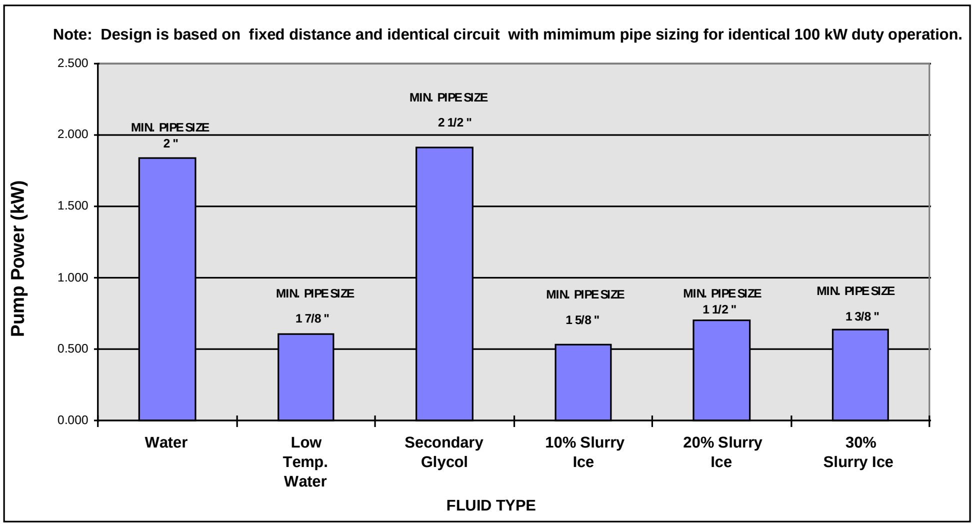


Figure 3.3.3.2 Pump Power Study for 100 kW Duty

An R&D program at the National Research Council in Ottawa has shown in stop / start tests that agglomeration and compacting / solidification of the slurry ice does not occur in water where glycol is used as freeze depressant. In this study, the flow was repeatedly stopped for periods from 10 s to 10 min. No difficulties were observed when the flow was restarted. However, special consideration must be given to all vertical pipe runs in order to overcome any agglomeration with in the pipe circuit.

3.3.4 Fittings and Valves

Existing experimental studies as well as the installed slurry ice loops utilised a wide variety of common commercial pipe fittings, including elbows, tees, couplings, bushings, and reducers. Ice fraction limitations due to plugging resulting from the presence of these fittings have not been observed in any slurry ice research and site installation.

If the system does not contain any sharp reductions in the flow cross section, the use of fittings for slurry ice applications should pose no problems but the size and the shape of the ice crystals must be taken into account for the selection of control, solenoid, isolation, regulating, check valves as well as the special requirement for the strainer/filter arrangements in order not to cause malfunctioning and clogging.

It essential to select the line components for the temperature ranges at which the slurry is circulated and the internal construction of these line components must be investigated further for slurry-ice operation. A line component which has an internal vertical riser such as regulation valve chamber which may be clogged during stagnant and reduced flow conditions, could cause extra pressure drop or even complete blockage.

4.0 SLURRY ICE DISTRIBUTION

A significant part of the initial investment cost for any large scale central cooling system is the pipework distribution network and therefore any reduction in pipe sizes represents a significant cost reduction of the distribution system. The economic advantage gained from a reduction in the pipe diameter results in lower capital costs, and lower operating costs. The operating costs are reduced due to lower pumping energy requirements and the reduction in heat gains. Although an slurry ice based system can operate with reduced diameter distribution networks, the system should be designed to accommodate future expansion.

The improvement in “cooling” capacity achieved by the latent heat of an ice fraction within the pipeline relative to chilled water as shown in Figure 3.2.2 results in the pipe cross section reduction by a factor of approximately four for an ice fraction of 0.20. This is equivalent to a diameter reduction by a factor of about two. Since the cost of pipe and installation increases more or less linearly with diameter , major savings in capital investment can be achieved by using slurry ice.

Furthermore, the diversity factor may offer the designers additional pipeline size reduction depending on the application. This diversity factor quantifies the decrease possible in the installed chilling capacity of a large scale energy system because of the small likelihood of all loads having a co-incident peak demand. Depending on the configuration of the piping network and storage tank arrangement, the load diversity may permit the use of reduced diameter pipes, especially in pipes close to the pumps. It must be realised that the total energy requirement of the system remains unchanged. Therefore, the diversity factor cannot be applied to reduce the chiller capacity in cases where the load is levelled by central or distributed storage.

4.1 Pipeline Transport of Slurry ice

The perceived concern associated with pumping slurry ice through pipelines is potential plugging due to ice agglomeration. However, from the research conducted to date and sites installed to date it appears that slurry ice can be safely pumped through pipelines within a certain envelope of ice fractions and Reynolds’ numbers. The recommended parameters are shown in Figure 4.1.1. Ice fractions above 0.25 requires further design considerations and when transporting slurry ice, velocities should be maintained above 0.5 m/s. It is expected that further design and practical field experiences will enable the designer to utilise higher ice fractions safely for large scale cooling systems.

A typical pipe sizing exercise is prepared in Figure 4.1.2 for various fluid options for an identical 100 kW duty. A fixed pipe size of 2” is used for the exercise in order to illustrate the pressure drop, flow rates and pipe velocity impacts but for a new installation, pipe sizes must be adjusted to the most economical sizes which appropriate for each section of the selected fluid type.

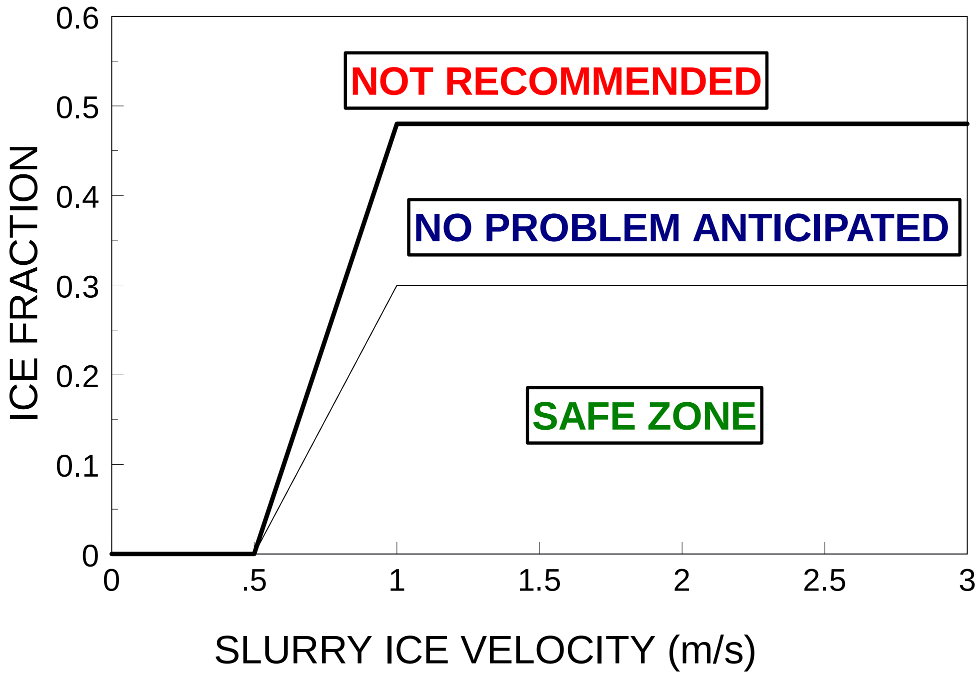


Figure 4.1.1. Slurry Ice Velocity Vs Ice Fraction Study

In the case of pump or power failure, the flow in the system or part of the system stagnates, the ice will float to the top of the pipe due to buoyancy. Local ice fractions caused by buoyancy forces alone should not exceed 0.30 ice fraction. For an initial 0.20 ice fraction, it is expected that almost one-half of the flow area will be available for the flow when it is re-established.

There are three possibilities for the ice at the top of the pipe to be re-incorporated into the flow. For the small expected ice fraction of the agglomerated ice pack, it is most likely that the turbulence in the flow will cause the ice particles to be re-distributed. Otherwise, the agglomerated ice pack will move as a unit along with the flow beside it, and will break up at the first bend or fitting. A combination of the two is also possible. In the worst case scenario, a very serious blockage of a pipe will ultimately correct itself within a few hours, as the heat gains will eventually melt the ice.

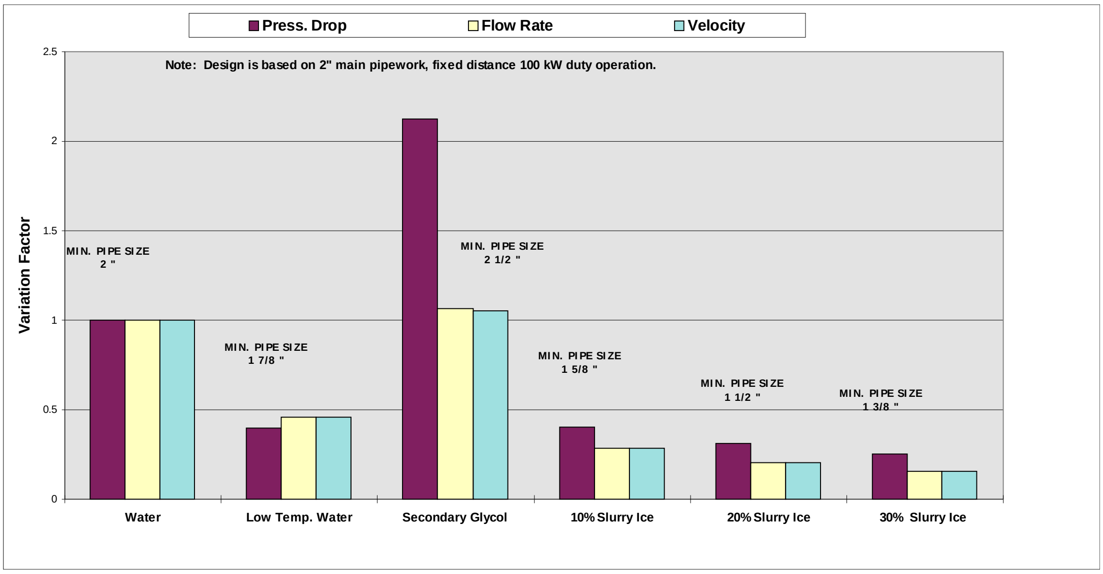


Figure 4.1.2 A Typical Pipe Sizing Study for Identical 100 kW Operation

The distribution pipework system of a large scale cooling system must deliver the slurry ice to different loads with a wide range of flow requirements. Therefore, the ability to split the slurry ice flow while maintaining a uniform concentration is important. Existing sites and test studies have not encountered any problem when slurry ice was split and transferred through two parallel sections. The fine ice crystals have negligible body forces relative to the turbulent diffusion within the flow itself and it is reasonable to expect that the ice will distribute uniformly in both legs as the flow is divided.

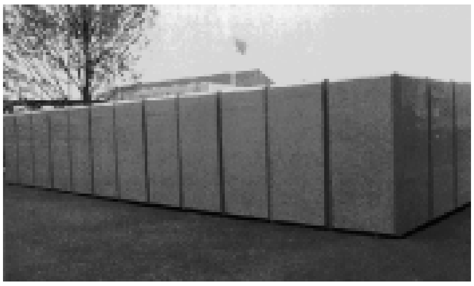
4.2 Slurry ice Vessel

The most economical way to utilise the **Slurry-Ice** concept is the distribution of peak loads over a 24 hours or even a weekly/seasonal cycle in which a small ice machine can be used to satisfy large peak demands. The pumpable characteristic of **Slurry-Ice** offers the designers the flexibility of shape, size and location for the ice storage tank.

CFC-free pre-insulated **Glass Reinforced Polyester (GRP)** sectional rectangular and factory finished cylindrical tanks can be utilised to suit almost every application, including the dry ice crystal harvesting systems. The encapsulated pre-insulation should provide at least an insulation thermal conductance of 0.55 W/m^2 maximum. If the design requires a concrete tank installation, a suitable tank pipe sealing system must be selected in order to handle the temperature variations for trouble free operation.

Glass Reinforced Polyester (GRP) sectional tanks can be designed for site assembly for application flexibility and all storage tanks ***MUST COMPLY*** with all local Water Bylaws.

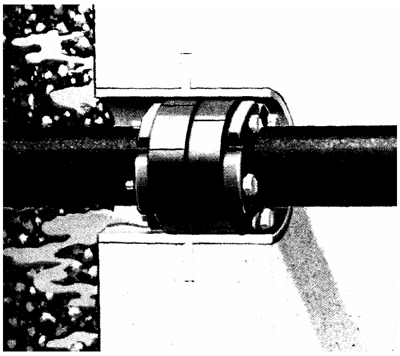
It is recommended that a CFC-free pre-Insulated GRP tank complete with Totally Internal Flange (TIF) construction concept is implemented in order to achieve tight space application and sweat-free operation.. The appearance of the tank is also most aesthetically pleasing and the design is such that the tanks panels should be fully insulated flange to flange. Slurry-Ice ice storage vessels must be supplied complete with Manway Access, Screened Cowl Vent, Overflow and Screen and the essential system solution / Slurry-Ice spurge pipe arrangement to suit the application.



Slurry-Ice is lighter than the solution and as such tends to float at the top of the tank. Hence, vertical cylindrical CFC-free pre-Insulated GRP tanks offers the smaller foot print area and maximum ice storage capacity. Horizontal tank arrangements can be supplied for special applications. A custom design dry ice crystals harvesting type CFC-free pre-Insulated GRP tanks can also be applied for dry crystal ice application, in particular for the food and process industry

Concrete tank applications require careful consideration regarding the contraction ratios of various tank materials. In particular, the pipe sealing system must be capable of providing leak free operation for varying solution temperatures. A suitable pipe sealing system must be installed for either the conversion of an existing or alternatively a site-built customised concrete tank installation

The major technical challenge is to keep the ice in the concentrator fluidised. This fluidisation can be accomplished in different ways. The first option is to install mechanical mixers but the drawback of mechanical mixers is that they add energy to the system and thereby decrease the efficiency. Enough mixers must be installed to ensure that the entire mass of ice remains fluidised and that no stagnant pockets persist. Alternatively, a passive technique by means of utilising warm return solution for the same function described above.



4.3 Pipe Network

Any commercially available pipe materials for chilled water system can be used for slurry ice application as long as the operating temperature and pressure limits are observed. Numerous plastic and fibreglass as well as pre-insulated piping materials have become available in recent years and they can be used for slurry ice systems.

The cooling capacity of slurry ice is much greater than that of cold water but insulation requirements do not necessarily become more stringent. Depending on the use of freeze depressants and their concentration, the temperature of the liquid remains close to the freezing temperature, independent of the ice fraction. With slurry-ice based systems, the temperature difference between surrounding air, soil or liquid remains small.

The return line of a slurry ice system may not necessarily may not require insulation for certain applications with water at ≈13^{0}C, even if it is cost effective to insulate the supply line.

4.4 Mechanical Conveyor System

The higher slurry-ice concentration levels, and in particular dry crystal ice distribution systems, requires careful design of a customised transport system. High ice concentrations up to 80-90 % ice fraction can be pumped utilising special pumps.

Dry crystal ice can be transported either utilising an automatic mechanical conveyor system, or manually, by means of harvesting from the central storage tank and loading into containers for forklift transport. If the ice application tolerates water content, the dry ice crystals can be mixed with water to a desired concentration level and pumped directly to the process.

4.5 Operating Strategy

Four operating strategies have been developed to avoid having to restart the flow of slurry ice during normal operations.

4.5.1. Constant Flow / Variable Ice Fraction_**(Strategy 1):**

This technique can be used in systems without thermal storage or with central thermal storage. The design premise is to maintain a constant flow at all times in the distribution network while optimising the thermodynamic efficiency of the system by maximising the evaporation temperature.

The maximum thermodynamic efficiency is obtained when the return leg of the system is maintained at a maximum temperature. Changes in cooling load are accommodated by adjusting the temperature or ice fraction in the supply leg.

For example, consider a system operating at its design capacity with 20% ice fraction supply and 13^{0}C return. If the cooling load decreases, the temperature of the return stream will drop. In the simplest operating mode, the system responds by lowering the ice fraction in the supply stream while keeping the flow constant.

Further reductions in the cooling load will result in lower ice fractions until only chilled water is required to meet the load. With further load reduction, the flow will be decreased. The advantages of this option are constant flow (down to 0% ice) and maximum thermodynamic efficiency.

In some cases, the cost of pumping may be significant. Therefore, in a given situation it must be considered whether it may be financially more attractive to lower the flow at a given slurry ice percentage. It must be remembered to maintain the slurry ice velocity above the minimum required for proper slurry ice fluidisation.

4.5.2. Purge and Stop_**(Strategy 2):**

This control option can be used on system with distributed thermal storage. The distributed thermal storage concept, which is presented in detail in Section 5.1.1, eliminates the need for part-load operation. The ice generation system is either on or off. When ice generation is no longer required, water is circulated through the system to purge the ice prior to stopping the flow.

As mentioned earlier, unforeseen circumstances may still cause a shut down of the distribution system in the fully charged condition. Therefore, the following guidelines should be observed to minimise the problem.

1. Avoid long vertical piping runs. The higher the fluid column the more severe the stratification.
2. Oversize the distribution pumps. Use variable speed drives to maximise performance.
3. Provide redundant pumping equipment designed for rapid deployment.
4. Provide an emergency power supply for the pump and other critical components

4.5.3. Dry Ice Crystals/Water Mixing Pumping **(Strategy 3):**

This technique is based on mixing dry ice crystals which are normally harvested from the top of the Slurry-Ice storage tank in to the mixing tank. A mixing tank consists of dry ice crystals connection, water supply and agitator, in order to maintain the desired ice concentration level. The mixture of dry ice crystals and water is later pumped through a central delivery system to serve the work stations as required. Any unused ice mixture returns back to the mixing tank for recirculation.

Up to the delivery point that ice meets the product, this type of system is entirely sealed to minimise loss of cooling power. Not only is contamination avoided by means of the Slurry-Ice/water mixing technique, but a fully automated ice delivery system can also be achieved for higher productivity level.

4.5.4. Mechanical Removal System **(Strategy 4):**

Solution free dry ice crystals are formed at the top of the storage tank. If the dry ice crystals/water mixing technique is not applicable or capital cost does not allow such a system to be implemented, a rotating harvester can offer dry ice crystals removal. The free flowing ice crystals can be harvested whenever required from the discharge chute.

The transport of the harvested dry ice crystals can be achieved either utilising a mechanical conveyor system or manually, by means of open containers.

However, the sealed system efficiency and productivity benefits offered by a dry ice crystals/water mixing technique, are compromised if mechanical removal of the dry ice crystals is selected.

5.0 SLURRY-ICE STORAGE

5.1 Thermal Energy Storage Systems

Thermal Energy Storage ***(TES)*** is the temporary storage of high or low temperature energy for later use. It bridges the time gap between energy requirement and energy use. Most thermal storage applications involve a 24 hour storage cycle although weekly and seasonal storage applications are also used.

Storage Medium:

For HVAC and refrigeration application purposes, water and phase change materials (PCMs) constitute the principal storage media. Water has the advantage of universal availability, low cost and transportability through other system components.

Storage Strategies:

In full storage systems, the entire design load for the design day is generated off peak and stored for use during the following peak period. In partial storage systems, only a portion of the daily load is generated during the previous off peak period and put into storage. During the peak period, the load is satisfied by simultaneously balancing the operation of the installed machinery and the stored energy, in order to satisfy the overall daily design duty.

A conventional air conditioning thermal energy storage application generally utilises conventional chillers to build ice in order to match the demand by means of various techniques i.e. Demand Limiting, Peak Shaving, Full or Partial Storage etc. Figure 5.1 illustrates the principal of conventional thermal energy storage technique for air conditioning systems.

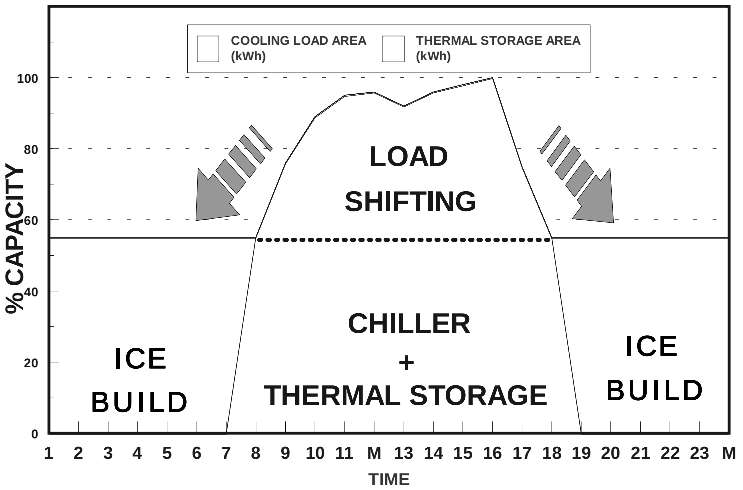


Figure 5.1 : A Typical Conventional Thermal Energy Storage Concept

5.1.1. Distributed Slurry Ice Storage

Centrally produced Slurry-Ice is distributed to and stored in a number of tanks located at each environmental and process (or group of environmental and process) location around the network. The slurry-ice enters the tank where the lighter ice crystals are separated, usually by gravity. Ice-free water from the storage tank may be used by the environmental and process cooling system as shown in Figure 5.1.1

The distributed storage tanks act like buffer vessels between the distribution system and the individual environmental and process cooling load requirements. This decoupling of the refrigeration system allows the distribution system to supply the average cooling load rather than the peak. If the average cooling load of an environmental and process system is much lower than the peak cooling load, reduced diameter size distribution pipes can be used.

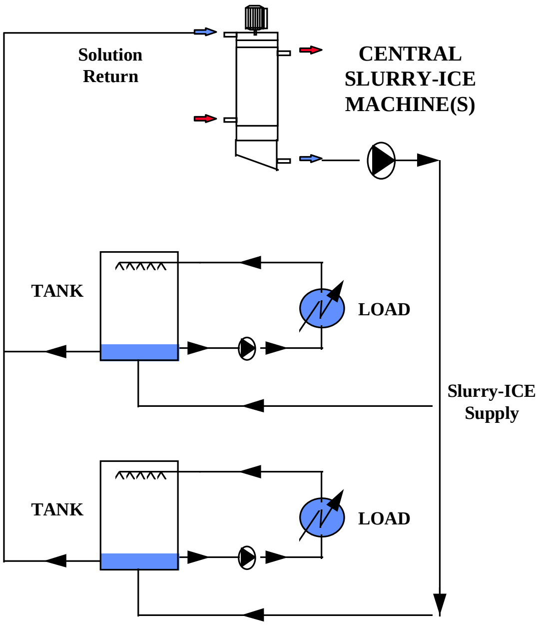


Figure 5.1.1. Distributed Slurry Ice Storage

The refrigeration system must generate slurry-ice continuously in order to meet the maximum design cooling load. This slurry-ice is pumped to the distributed storage tanks, which provide a buffer function. If the environmental and process cooling load is low, the Slurry-Ice will accumulate in the storage tank as the cooling load increases. The storage tank is simultaneously charged by the distribution system and discharged to meet the environmental and process cooling load.

During periods when the environmental and process load is reduced, the return water may be at a lower than optimal temperature with a certain amount of cooling potential still unused. The loss of this sensible cooling during part of the load curve means that the maximum enthalpy difference cannot be delivered to the storage facility continuously. Therefore, the distribution pipes must be designed for a capacity somewhat greater than the average load. A proper system simulation will determine the effect of unused cooling potential in the return water. When filling the tank during low load periods, the COP of the system may suffer due to low return temperatures. This problem can be (partially) rectified by raising the return water temperature by pre-cooling the ventilation air.

Generally, distributed storage will be most economical if the peak to average load ratio is greater than 2 and the latent to sensible heat ratio of the Slurry-Ice is greater than 1. Also, distributed storage becomes more attractive if the base load is substantial fraction of the average load, i.e., when then peak load is of short duration.

5.1.2 Central Slurry Ice Storage

A large scale space cooling system may require a central storage tank(s) located near the central refrigeration plant as shown in Figure 5.1.2.

Ice distributed storage, the advantage of providing a buffer facility between the refrigeration system and the actual cooling demand generated by the environmental and process on the network can be achieved by this technique. However, in central storage the distribution system is not decoupled.

The cooling capacity within the distribution system must follow the actual cooling demand.

This technique can be applied utilising two operating strategies. Slurry-Ice can be stored within the storage tank and utilised only to cool return water from the system for re-distribution.

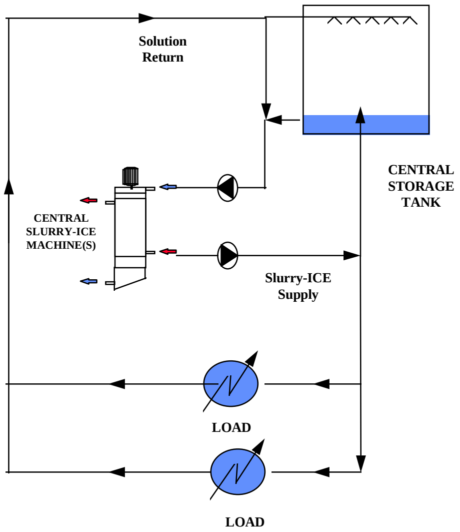


Figure 5.1.2. Central Slurry Ice Storage

Alternatively, Slurry-Ice can be stored and fluidised during peak hours for distribution. With both approaches, the volume of storage is reduced compared to chilled water storage. Distribution of Slurry-Ice during peak demand will additionally reduce the distribution network pipe diameters.

A storage system in which ice does not need to be fluidised or harvested may be preferable. The most cost-effective compromise may be to use storage to chill return water to 0^0C at the time of peak loads and mix this water with Slurry-Ice delivered directly from the chillers. The proportion of the load served by Slurry-Ice chillers will depend on the load curve.

To meet the maximum design cooling load, the refrigeration system must operate continuously. During periods of low or zero cooling load, the generated Slurry-Ice is delivered to the storage tank. As the cooling load increases, the flow of Slurry-Ice is gradually diverted to meet the cooling demand. The flow of Slurry-Ice to the storage tank stops altogether at the time of maximum load.

The Slurry-Ice is delivered to the cooling loads where it is melted and warmed to approximately 13^0 C before it is returned to the central plant. The flow of slurry delivered to the cooling loads is controlled to ensure that the total available cooling, per unit mass circulated, is removed. At peak loads, to recover the cooling capacity stored in the central storage tank, a portion of the warm 13^0C return water is directed through the tank. The ice stored in the tank is melted as the return water is chilled to the freezing point. The chilled water is then removed from the storage tank and returned to the distribution system. The remainder of the return water is directed to the chiller(s) as usual.

5.1.3 Dry Ice Crystal Storage

This technique is applicable for direct ice usage, mainly for food and process applications. A small slurry-ice machine is utilised over a 24 hour period to satisfy the peak shift ice consumption.

A conventional cylindrical tank concept can hold up to 60% of ice content which can be generated over 24 hours, but if the harvesting is required for a short production period, the stored ice can either be directly recovered from the central storage tank or alternatively on a continuous harvesting principle by means of mechanical removal and storage somewhere else in the system.

Both options offer economical ice production and storage options for the end users.

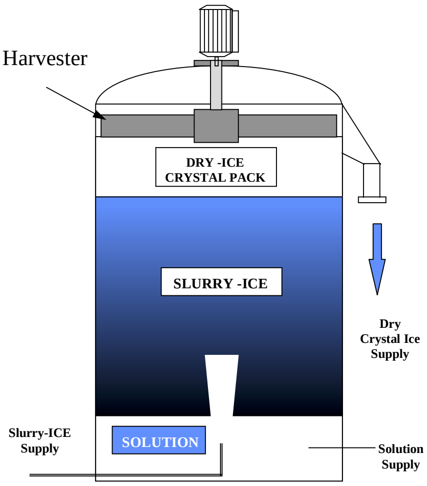
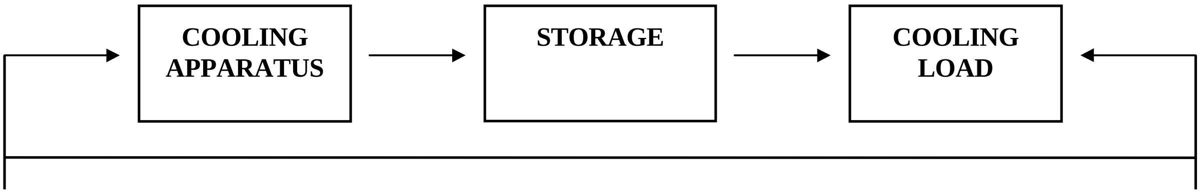


Figure 5.1.3 Dry Ice Crystal Storage

5.2 SLURRY-ICE STORAGE SIZING

5.2.1 Refrigeration Capacity

The cardinal rule of any slurry-ice storage sizing can be shown in the following fashion to satisfy the application.



"THE CAPACITY OF THE COOLING EQUIPMENT OVER TIME MUST BE EQUAL TO THE SYSTEM LOAD PLUS SYSTEM LOSSES OVER TIME"

The capacity of the installed refrigeration system is sized by summing the hourly cooling loads for each environmental and process serviced by the large scale cooling network for a "design" day.

The total integrated cooling load is then divided by the desired number of continuous hours of operation for the refrigeration equipment per day. (Typically, the number of hours per day of continuous operation is set at 20 to 22 h to allow time for routine maintenance). The result of this calculation is the peak average daily cooling load. The minimum installed capacity should be equal to this number.

5.2.2 Ice Storage Capacity

The required central storage capacity is calculated from composite hourly cooling load data for all of the environmental and process loads serviced by the network. Ice storage is required to store the excess capacity delivered to the storage tank during periods of low or zero cooling loads. The ice storage capacity is determined by integrating the hourly difference between the composite hourly system cooling load and refrigeration system capacity calculated above for the "design day".

For a distributed storage system, the ice storage capacity is determined for each environmental and process load individually. The slurry-ice delivery rate for each tank is then determined first. The method is similar to sizing the installed capacity for the entire system. For each load area, the slurry delivery rate is determined by integrating the hourly cooling loads and dividing by the desired number of hours of continuous operation. If maximum enthalpy difference cannot be maintained during periods of low load, the slurry delivery rate has to be adjusted to compensate.

The storage capacity is estimated by integrating the hourly difference between the actual environmental and process cooling load and the slurry delivery rate to the storage system for the "design day".

The actual storage volume also depends on the degree of ice packing, the room required for diffuser piping, harvesting equipment, room for expansion of the ice, etc.

5.3. Slurry-Ice Storage Tank Design

The most economical way to utilise the **Slurry-Ice** concept is the distribution of peak loads over a 24 hours or even a weekly/seasonal cycle in which a small ice machine can be used to satisfy large peak demands. The pumpable characteristic of **Slurry-Ice** offers the designers the flexibility of shape, size and location for the ice storage tank.

CFC-free pre-insulated **Glass Reinforced Polyester (GRP)** sectional rectangular and factory finished cylindrical tanks can be utilised to suit almost every application, including the dry ice crystal harvesting systems. The encapsulated pre-insulation should provide at least a insulation thermal conductance performance of $0.55\ W/m^2$. If the design requires concrete tank installation, a suitable tank pipe sealing system must be selected in order to handle the temperature variations for trouble free operation.

In principle, slurry-ice tanks can be any shape but most the commonly used designs remain rectangular or cylindrical. The storage tank can be placed either under, beside, inside or on top of a building. Slurry-ice floats at the top of the tank and therefore cylindrical tank designs offer the largest storage capacity and smallest footprint.

A slurry-ice storage tank design should take into account the buoyancy of the slurry-ice and therefore the slurry-ice and solution supply and return sparge pipes must be provided to achieve a uniform and steady ice building and melting process. The design should also incorporate all the necessary manhole, screen cowl, vent, overflow and drain connections.

5.3.1 "Free Liquid" Storage Tank Design

The "free liquid" storage tank design has been used extensively in single environmental and process thermal energy storage applications. It is typically a large, non-pressurised tank. The storage tank is filled to approximately 80% with water. As the Slurry-Ice enters the tank, ice crystals stratify and float to the surface of the liquid. The ice gradually accumulates from the surface of the storage tank down to the bottom of the tank.

Top Charging

The most common method of charging a "free liquid" ice storage tank is to supply the Slurry-Ice from the top using a simple distribution system above the liquid level as illustrated in Figure 15. The top charging configuration enhances the maximum ice fraction within the storage tank, minimising the size of this component. The weight of each successive layer of ice creates a compacting force as the ice pack tries to float on the surface. Continued charging forces the ice pack gradually downwards to the bottom of the tank. When the ice reaches the bottom of the tank, further ice production causes the liquid level to drop. The exposed ice is no longer partially supported by the water and hence ice is compressed further.

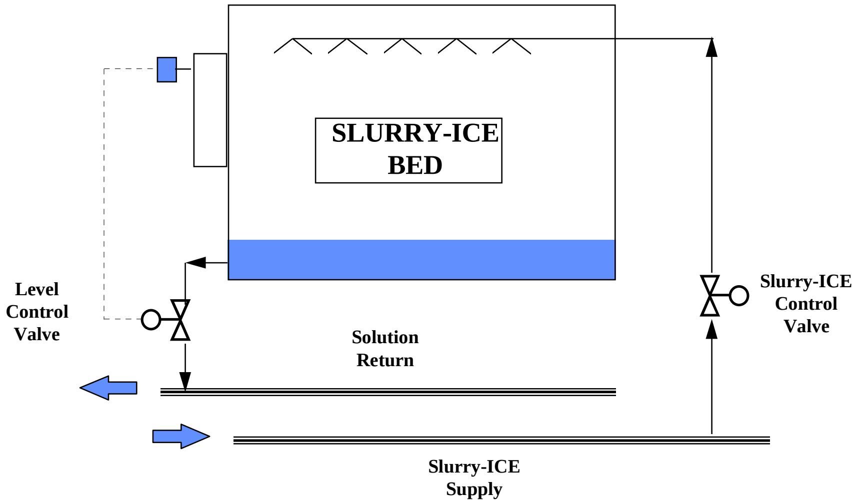


Figure 5.3.1 Free Liquid Slurry Ice Tank Concept

Bottom Charging
In the bottom charging method, Slurry-Ice is distributed across the bottom of the tank using a simple piping system. A bottom charging configuration relies upon the buoyancy of ice to push the ice pack up. Continued ice storage gradually causes the ice pack to reach the bottom of the storage tank. However, once the ice has reached the bottom, the distribution piping may be blocked, preventing further ice storage.

Tank Geometry
Several basic storage tank shapes are particularly attractive from a construction point of view. These include a horizontal cylinder, vertical cylinder and square tank. However, the physical characteristics of Slurry-Ice are more suitable to certain styles. Although the Slurry-Ice is delivered to the storage tank as a pumpable mixture, the Newtonian characteristic is lost soon after entering the tank.

The free liquid used to maintain fluidity during transport is quickly drained away when the ice and water separate by gravity in the storage tank. The ice pack is not a fused mass of ice. However, after the slurry enters the storage tank, an ice pack is formed with very little relative motion within the pack. Continued charging with ice will force the pack to move gradually as a thick mass.

Unless a bottom charging system is used, the horizontal cylinder is the least desirable geometry from an ice storage perspective. The curved sides of the vessel below the centre line provide a sub-surface support for the ice pack to rest upon. Consequently, the ice pack does not move as easily into the bottom portion of the tank, causing the ice to accumulate above the liquid. Eventually, the rising ice pack will block the slurry distribution piping, limiting the achievable ice fraction.

The vertical cylinder and square tank geometries can be considered together. The vertical sides of either tank style are favourable to bulk ice motion within the tank, enhancing the packing performance. The use of internal stiffeners should be avoided to eliminate barriers to ice pack motion within the tank.
In general, a taller tank can hold higher ice fractions than a shorter tank. It is expected that ice fractions up to 60% can be achieved in a properly designed storage tank.

Melting Stored Ice

Regardless of whether a top or bottom configuration is used to charge the "free liquid" ice storage tank, melting of the stored ice is typically the same. Warm water returning from the cooling load is sprayed over the top of the ice pack. The water is chilled as it filters down through the ice. Cold water is withdrawn from the bottom of the storage tank to return to the process. If the peak load is high and of short duration, a lot of ice may have to melt in a short period of time. The return water spray system must be properly designed to ensure this will occur. A uniform spray over the entire ice surface is preferred. A larger ice surface will accommodate a higher melting rate.

5.3.2 "Flooded" Storage Tank Design

The "flooded" ice storage tank design is a relatively new approach to Slurry-Ice storage. The storage tank is filled completely with water.

Slurry-Ice is pumped into the storage tank where the ice is filtered out so that the water leaving the tank is ice free. Since flooded storage tanks are pressurised, this concept is intended for use in a distributed storage system with multiple smaller tanks as shown in Figure 5.3.2.
The system has several advantages over conventional "free liquid" designs. The increase in ice fraction in storage and the simplification of the controls are advantages. The possibility of short circuiting the return water between inlet and outlet should be avoided.

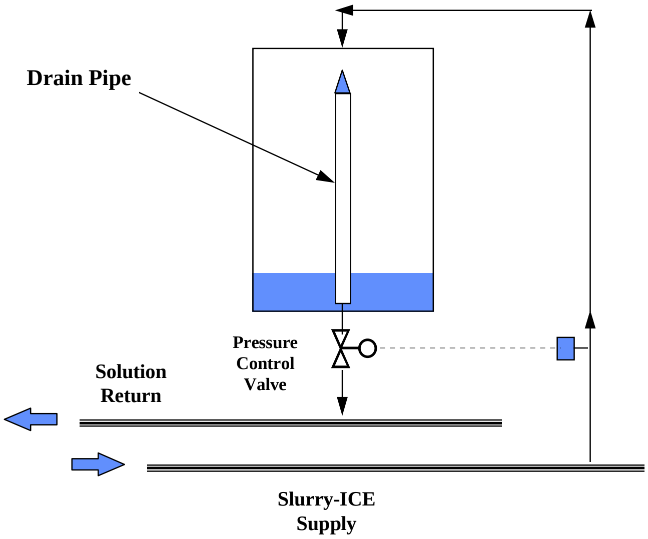


Figure 5.3.2. Flooded Slurry Ice Storage Tank Concept

Increased Ice Fractions

The ice fraction in "flooded" storage is improved by utilising the entire volume for ice storage. Unlike "free liquid" tanks which have a vapour space above the liquid (typically 20% of the total volume), the entire "flooded" storage tank is available for ice storage. However, a typical flooded storage tank system requires expansion vessels.
The ice fraction is also improved by using hydraulic forces instead of gravitational forces to pack the ice into the tank. The "flooded" ice storage tank is essentially an ice filter. The entering Slurry-Ice is filtered allowing only ice-free water to leave. Like most filters, the pressure drop across the tank will rise as the ice fraction increases. The limit of the maximum ice fraction will essentially depend on the maximum pressure drop across the tank.

Expansion Tank

The "flooded" storage tank concept requires an expansion tank to accommodate the increasing volume of fluid within the system as ice is produced. Conventional "free liquid" storage concepts accommodate the expanding volume within the vapour space at the top of the tank.

Melting Stored Ice

The "flooded" storage tank design simplifies the charging aspect of the problem. However, the discharging of the ice is complicated by the lack of an obvious method of ensuring good contact between

the warm water returning to the storage tank and the ice stored inside. The ice crystals within the storage tank will still tend to float to the top of the tank. Therefore, locating the warm return water distribution system in the upper portion of the tank will ensure good contact even when the ice content is low.
A bottom cold water outlet is also most desirable since the colder water is more dense and should accumulate in the lower portion of the tank. Water has its maximum density at 4°C.

Construction Limitations

The physical geometry of a “flooded” storage tank is less critical than that of the “free liquid” design. The ice is packed using hydraulic rather than gravitational forces. The primary design consideration is the pressure drop across the vessel.
The cost impact resulting from a pressurised design can be minimised by operating the tank at less than 200 kPa. Even using this modest differential pressure, the compressive force can be three to six times higher than that of conventional designs. The pressurised design also favours cylindrical storage tanks of smaller diameter to minimise shell thickness. The concept may be particularly well suited for the distributed storage operation with many smaller storage tanks.

5.3.3 Harvester Tank Design

Mechanical recovery involves harvesting and re-incorporating the ice stored in the tank into the distribution network. The basic concept requires a system of mechanical augers which move within the ice storage tank to scrape the ice crystals out of storage and convey them to the suction of the distribution pump.

Ice harvester systems have been successfully applied utilising a rotating scraper at the top of the storage tank to remove ice crystals. This type of system is widely used to generate ice crystals for the fishing industry where salt brine has been the preferred freeze point depressant.
The crystals can be back washed with clean water to minimise the carry over of freeze point depressant.

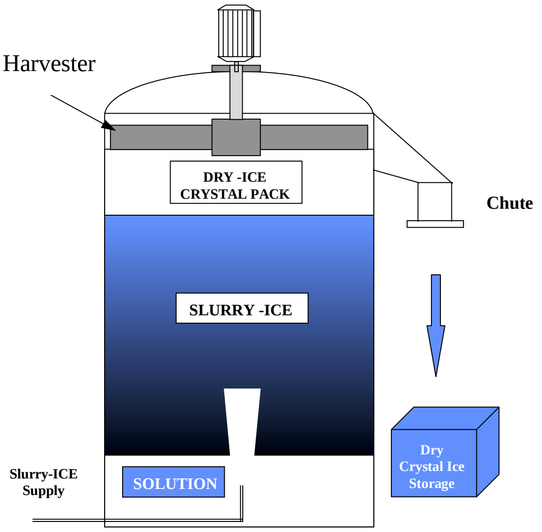


Figure 5.3.3. Harvester Tank Design

5.4 Additional Design Considerations

Another important design consideration is the requirement of low or no ice content in the liquid supply stream for some Slurry-Ice generators . To accomplish the withdrawal of ice free liquid for the Slurry-Ice chillers from a central storage tank, a portion of the storage vessel must be relatively free from turbulence. Turbulence free zone allows the Slurry-Ice to stratify, producing the desired ice free liquid source. The magnitude of the ice free liquid flow to the chillers may be higher than that of the Slurry-Ice supply to the network, increasing the difficulty of the problem.
A source of the ice free liquid for continued ice production can be obtained from the bottom of the vessel near the perimeter. A false bottom in the vessel composed of a coarse screen material can help to maintain an ice free liquid source below. In addition, the large cross sectional area of the screen minimises the maximum downward velocity, thereby further reducing the possibility of ice entertainment.

6. RECOVERING STORED COOLING

Two basic techniques, namely mechanical and passive, have been proposed to recover cooling from storage. Each is discussed in detail below.

6.1. Mechanical Technique

Mechanical techniques for recovering stored cooling from an ice storage tank have been discussed for some time. Research is ongoing to test the viability of different concepts.
Mechanical recovery involves harvesting and re-incorporating the ice stored in the tank into the distribution network. The basic concept requires a system of mechanical augers which move within the ice storage tank to scrape the ice crystals out of storage and convey them to the suction of the

distribution pump. This type of approach has been successfully employed for removing granular solids such as sugar and grains from storage silos.

The storage technique is strongly affected by the method of Slurry-Ice generation. Pure Slurry-Ice has been observed to agglomerate as the crystal to crystal pressure in storage can result in partial melting and re-crystallisation. However, slurry generation systems using Glycol or similar freeze point depressants appear to store well with little or no agglomeration.

Ice harvester systems have been successfully applied utilising a rotating scraper at the top of the storage tank to remove ice crystals. This type of systems are widely used to generate ice crystals for the fishing industry where salt brine has been the preferred freeze point depressant. The crystals can be back washed with clean water to minimise the carry over of freeze point depressant.

6.2 Passive Technique

The passive technique for recovering cooling from the ice storage tank eliminates the need for harvesting and re-incorporation of the ice. The cooling capacity stored in the Slurry-Ice is simply recovered by melting the ice. The warm water returning from the cooling load is sprayed over the ice pack in the storage tank and chilled prior to entering the ice generator. In this manner, the stored cooling is utilised without manipulating the ice.

Although Slurry-Ice from pure ice generation techniques can agglomerate into a semi-solid block, the ice appears to remain porous enough so that water can percolate through the ice particles to melt the ice and be chilled before it is returned to the system.

6.3 Operating Strategy for Central Storage

During periods of high demand for cooling, the storage reservoir should be charged with ice whenever possible. During periods of low cooling demand, the ice can be left in storage and the large scale cooling network operated with cold water from the conventional chillers because it is more cost effective to produce cold water than ice. The 13-15⑤C water from the return line of the large scale cooling system should be chilled by conventional means up to the base load demand. Any conventional capacity beyond the base load would be idle when the storage reservoir is being replenished with ice during base load hours.

7.0 SLURRY ICE UTILISATION

The use of slurry-ice in large scale cooling systems can dramatically affect the distribution pipe size and pumping power requirement. However, using an slurry-ice in existing processes designed for chilled water requires additional consideration. Three implementation strategies are described - direct Slurry-Ice, distributed storage and warm water recycle.

7.1 DIRECT SLURRY-ICE CONCEPT

The direct Slurry-Ice method involves sending the slurry-ice from the distribution pipe directly to the cooling coils as shown in Figure 7.1. Initially, this may appear to be the simplest approach for implementing Slurry-Ice at the end user. However, the technical problems associated with this concept may require further attention. Existing heat transfer equipment installed in large environmental and process applications is designed for chilled water, not Slurry-Ice service.

A direct conversion of existing chilled water equipment into Slurry-Ice service would result in a lower internal heat transfer co-efficient, an increased temperature difference and create a potential for ice blockage within the heat exchanger. Experiments with plate heat exchangers and other operating experience indicates that the potential for ice blockages in this kind of equipment is very limited.

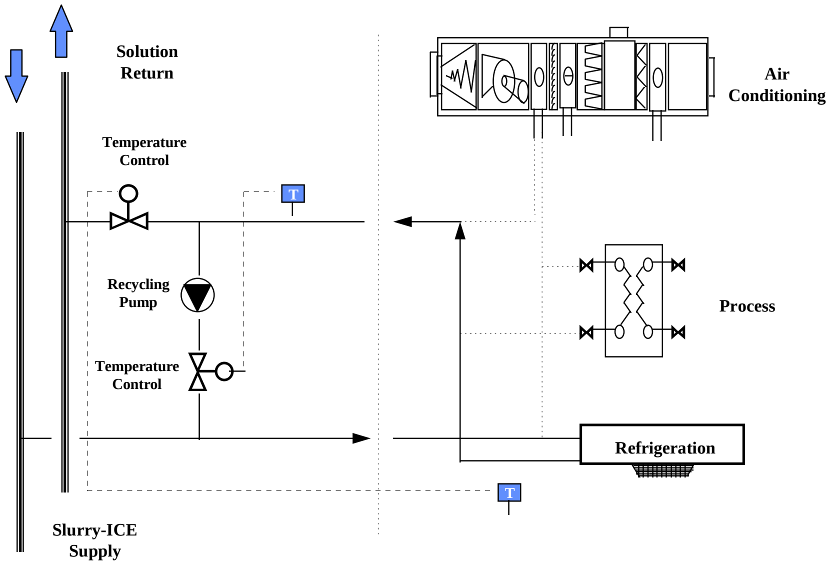


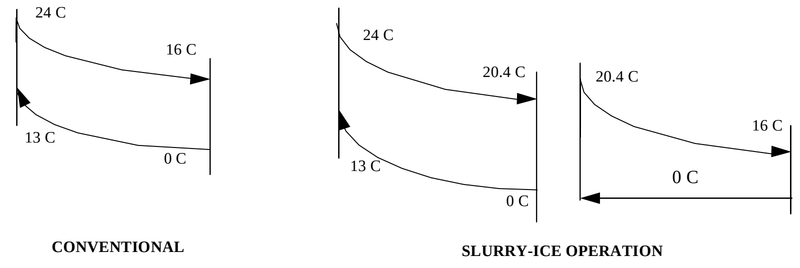
Figure 7.1. Direct Slurry Ice Application

7.1.1. Decreased Heat Transfer Rate;

The increased energy carrying capacity of slurry-ice will substantially decrease the required flow rate to meet a given cooling load. Even a modest ice fraction of 20% will reduce the flow rate by a factor of 5.2 in chilled water cooling coils originally designed for a temperature differential of 6^0C. The reduced flow rate translates directly into a lower fluid velocity inside the exchanger.
The heat transfer co-efficient within a tube or coil is proportional to the Reynolds and the Prandtl numbers and if the Prandtl number can be taken as a constant and the change in the Reynolds number will be limited to velocity effects only. Under these assumptions, the internal heat transfer co-efficient would be proportional to the reduction in velocity. Consequently, the internal heat transfer co-efficient will be reduced by a factor of 3.7 for a chilled water coil originally designed for a 6^0C temperature difference, when operated with 20% Slurry-Ice.
The final impact of a lower internal heat transfer co-efficient on the actual cooling capacity of the coil will depend on the combined effects of internal and external heat transfer coefficients on the overall heat transfer co-efficient.

7.1.2 Increased Temperature Difference;

The temperature difference between the air and slurry will be greater than the original air to chilled water difference. It should be verified that the magnitude of this increase is sufficient to offset the reduced heat transfer co-efficient due to lower velocities described above. The log mean temperature difference (LMTD) for both cases must be taken in to account.
Assuming that the air side of the exchanger remains unchanged, the impact of the slurry is limited to an isothermal behaviour for part of the duty, and lower temperatures throughout. To analyse this situation correctly, the heat exchanger should be divided into two sections, where the latent and sensible heat of the slurry is recovered as shown in Figure 7.1.2.



CONVENTIONAL

SLURRY-ICE OPERATION

Figure 7.1.2. Log. Mean Temperature Impact

The latent heat of a 20% Slurry-Ice represents approximately 55% of the available cooling. The balance is sensible heat. With this in mind, the weighted average LMTD for Slurry-Ice is 16.8⑤C. This is a significant increase in LMTD for the Slurry-Ice. The larger LMTD will augment the heat transfer to balance the negative effects of the reduced internal heater transfer co-efficient..

7.1.3 Slurry-Ice Blockage;

The small flow passages in many high efficiency heat exchangers may be susceptible to blockage from the Slurry-Ice if the flow paths are not uniform and continuous. Stagnant fluid pockets typically found at the end of piping manifolds may allow ice to accumulate and eventually plug the flow. This problem may be further aggravated by the low velocities which could exist in this situation. A flow blockage caused by Slurry-Ice is self-healing when the ice melts.

7.1.4 New Heat Exchanger Design

To alleviate the problems of converting existing chilled water equipment for Slurry-Ice service, new heat transfer equipment specifically designed for use with Slurry-Ice could be installed. In particular, a conversion from a direct expansion coil to slurry-ice operation must be carefully studied and considering the header site modifications and cost associated with this work, it may be more economical to replace direct expansion coil with a slurry-ice coil.

7.2 DISTRIBUTED ICE STORAGE CONCEPT

Once solution to overcome the potential problem associated with sending Slurry-Ice directly into conventional air-handling equipment is to implement distributed ice storage. The local ice storage tank is then used to separate ice from the carrier water ice free water can then be pumped from the storage tank and delivered to the air handling equipment, as illustrated in Figure 7.2

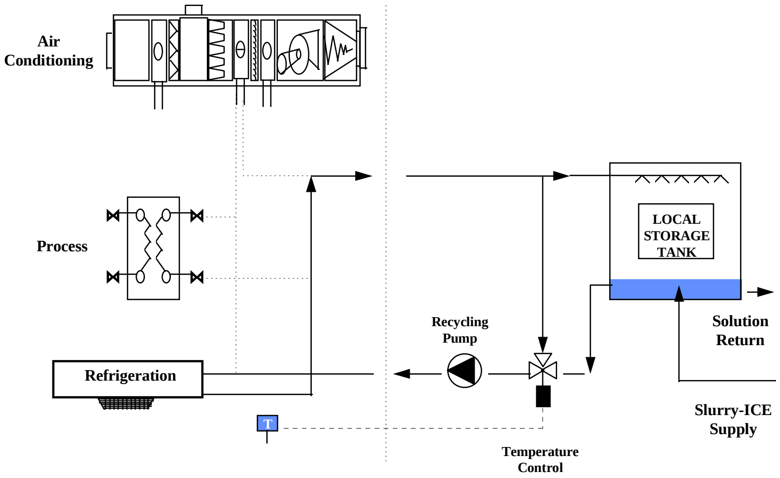


Figure 7.2. A Typical Distributed Slurry Ice Application

The flow rate of the cold water can be selected to match the design requirements of the existing chilled water equipment. Similarly, the design inlet temperature requirements can be matched by installing a mixing valve upstream of the circulation pump. One part of the warmed water leaving the heat exchanger is returned to the ice storage tank for re-chilling as the water passes through the ice pack. The other part is re-circulated with the cold water entering from the tank.

The distributed ice storage technique is a relatively simple way to integrate Slurry-Ice without affecting the operation of existing heat transfer equipment. Distributed ice storage also provides a simple means of load levelling.

7.3 WARM WATER RECYCLED SLURRY ICE CONCEPT

The warm water recycle concept was conceived to facilitate the use of ice slurries without affecting the design conditions of existing heat transfer equipment, while eliminating the need for local ice storage. The basis of the idea is to transform a low flow, high cooling capacity Slurry-Ice into high flow, lower cooling capacity chilled water.

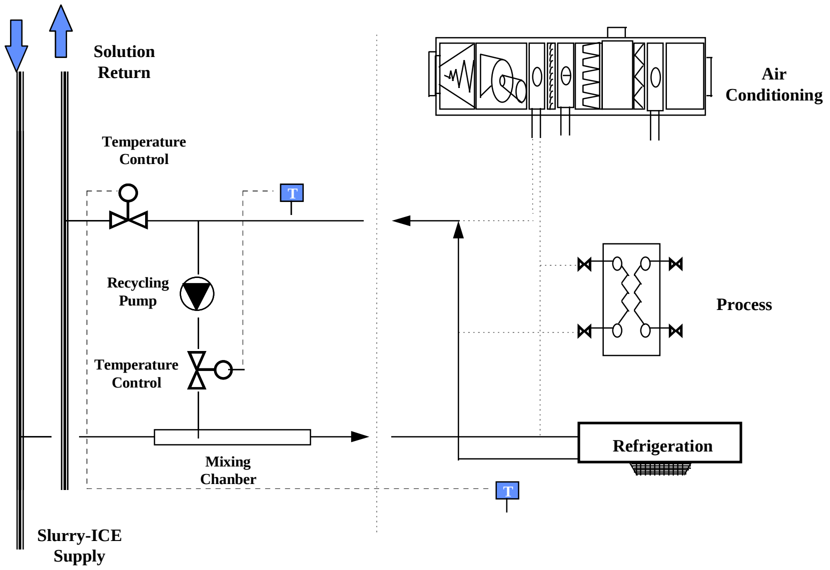


Figure 7.3.A Typical Warm Water recycled Slurry Ice Application

The method involves the use of a warm water recycle stream from the discharge of the heat exchanger as shown in Figure 7.3. The warm water is mixed with the incoming Slurry-Ice to completely melt the ice and produce the desired flow rate and design inlet temperature. In this way, the exact design conditions of both flow and temperature can be matched for each specific end user around the entire large scale cooling network.

7.4. SLURRY ICE SUPPLY / RETURN HEAT EXCHANGER CONCEPT

This technique involves the use of a warm water capacity by means of slurry-ice supply to warm water return heat exchanger. It is in principle identical to suction to a liquid heat exchanger for the direct expansion refrigeration. The heat exchange rate is dictated by the load on the cooling coil. A simple diverting valve on the return line should ensure a sufficient amount of slurry-ice passes through the heat exchanger to satisfy the cooling load, which must be taken away by the return water.

Hence, the system can be considered a self balancing heat exchanger and in case of no duty requirement, the supply slurry-ice can be bypassed and returned back to the storage tank. This technique simplifies the operation and the lack of an additional circulation pump means less maintenance.

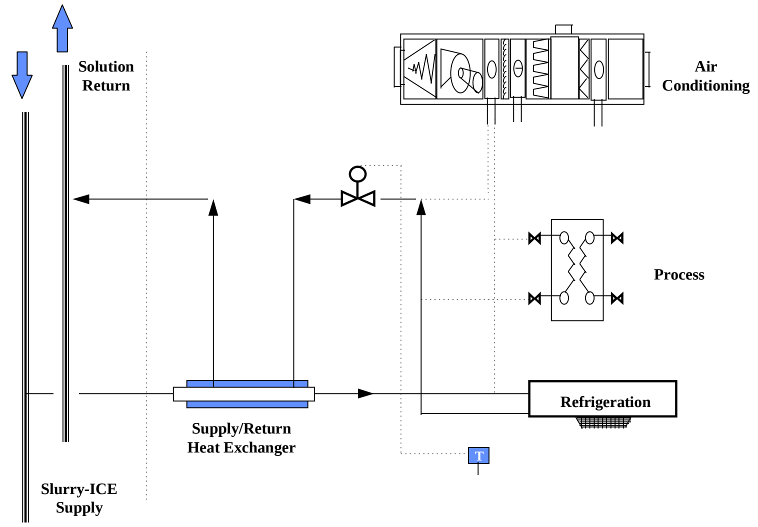


Figure 7.4. Slurry Ice Supply/Return Heat Exchanger Application

8.0 CONTROLS

It is vital to provide properly functioning and suitable control systems for satisfactory operation. The necessary control valves and controls must be selected based on the type of solution and temperature range. This section describes possible commercially available techniques for accomplishing satisfactory control of the cooling energy delivered by the slurry ice to a load.

8.1 Control Valves

The use of conventional control valves such as conventional needle, sliding gate, diaphragm and globe valves into any type of slurry service is not recommended.

Some speciality valves have been developed for use in other slurry systems which may be applicable to Slurry-Ice service. The best solution is to avoid installing control valves in Slurry-Ice lines altogether. Section 7 contains system strategies which effectively eliminate the need for control valves in Slurry-Ice supply lines. The strategy is to install control valves on the warm water return side of the system.

8.2 Controls for Central Storage Tanks

To maintain accurate control of the central storage system, the ice fraction in the storage tank must be known. Ice fraction instrumentation based upon a low cost conductivity transmitter have used to provide a reliable indication of the overall ice fraction within fresh water slurry-ice system. Optical systems may also be used for the same function.

To maintain the correct level in a “free liquid” storage tank, the flow of Slurry-Ice into the storage tank must be balanced by the flow of ice-free water out of the storage tanks, for return to the distribution network. No proportional flow control on the Slurry-Ice supply is required. The refrigeration system is decoupled from the actual cooling loads imposed by the users. The ice storage tank is charged in an on/off mode of operation. The flow of water pumped out of the storage tank back to the distribution systems can be controlled with a level transmitter mounted on an ice free standpipe on the side of the tank and a flow control valve.

The controls of the “flooded” storage tank are simplified by eliminating the second pump and liquid level control loop associated with conventional “free liquid” storage tanks. The flow into the storage tank is equal to the flow out.

8.3 Controls for Slurry Delivery

Typically, for environmental and process air conditioning applications, the temperature of the air leaving the cooling coil is the critical control point. The flow of chilled water is regulated to maintain the desired air delivery temperature. For a direct Slurry-Ice system, the air delivery temperature is still the critical control point. The desired air delivery temperature must be maintained by regulating the flow of the Slurry-Ice entering the cooling coil.

The warm water recycle technique requires two control loops. The first control loop regulates the flow of Slurry-Ice into the mixing section where the ice is melted by the recycling warm return water. This happens just upstream of the coil that cools the air delivered to the environmental and process load. The slurry flow is controlled indirectly by restricting the flow of warm water returning to the distribution system. Installing the control valve in the warm return pipe eliminates the uncertainty of installing a control valve directly in the Slurry-Ice lines.

The second control loop maintains the desired temperature of the warm water exiting the heat exchanger. Sustaining the highest possible return temperature is critical to optimising the performance of the Slurry-Ice distribution system.

The warm water exit temperature is controlled by regulating the flow of warm water in the recycle stream to increase the inlet temperature at the cooling coil. If the exit temperature of the heat exchanger begins to drop, due to a reduction in cooling load, the return flow of warm water is reduced. The result is a decrease in the amount of Slurry-Ice entering the mixing zone. The temperature of the flow entering the coil therefore increases. The warmer inlet temperature effectively reduces the cooling capability on the cold side in response to the lower cooling load. If Slurry-Ice is used in the coil, the control valve should be placed in the warm water return line.

8.4 Controls for Distributed Storage Tanks

Distributed ice storage tanks provide a relatively simple means of eliminating Slurry-Ice handling at the end user. The controls for this approach are identical to any conventional chilled water air conditioning application with the addition of a mixing valve upstream of the coil to raise the inlet water temperature to avoid excessive dehumidification.

Depending on the load, a fraction of the return water from the heat exchanger is sent back to the local ice storage tank and some of it is recirculated. The remainder, being equal to the Slurry-Ice supply flow, is returned to the distribution system. The water outlet temperature must be controlled to maximise energy efficiency. It is possible that during periods of very low load and while the storage tank is being replenished, the maximum enthalpy difference between supply and return lines cannot be maintained. The large scale cooling pipe diameter must be sized to accommodate for this period of lower enthalpy delivery.

Additional controls at the central cooling system are required to monitor the quantity of Slurry-Ice in the storage tanks at all times. This information is essential to avoid running out of ice during peak cooling periods.

In summary, the necessary controls to facilitate the operation of a large scale slurry-ice cooling system are available and their implementation is fairly routine.