Available online at www.sciencedirect.com
SCIENCE DIRECT®
International Journal of Refrigeration 28 (2005) 4–12
REVUE INTERNATIONALE DU FROID
INTERNATIONAL JOURNAL OF
refrigeration
www.elsevier.com/locate/ijrefrig

From physical properties of ice slurries to industrial ice slurry applications

Peter W. Egolf*[,a], Michael Kauffeld[b]

[a]University of Applied Sciences of Western Switzerland, CH-1401 Yverdon-les-Bains, Switzerland
[b]Karlsruhe University of Applied Sciences, D-76133 Karlsruhe, Germany

Received 5 February 2003; received in revised form 10 June 2004; accepted 17 July 2004

Abstract

The use of ice slurries dates back many millenniums, e.g. the ancient Romans applied the cooling of snow-water and ice-water mixtures. Approximately two decades ago a breakthrough of the new technology of producing ice slurries has set in the refrigeration domain for the cooling of shops and supermarkets. After some difficulties at the beginning, it is now possible to build systems, which operate as designed. However, there is still a huge potential to lower the energy consumption and the costs of the systems. Actions in this direction are the design of new ice slurry generators, the development of new concepts for storage and mixing, etc. In this article a short review of the basic research on ice slurries is presented. Furthermore, practical problems of the application of the technology in refrigeration and process techniques are discussed.

Keywords: Two-phase secondary refrigerant; Ice slurry; Survey; Research; Example; Manufacturing; Refrigeration system

Coulis de glace: propriétés physiques et applications industrielles

Mots clés: Frigoporteur diphasique; Coulis de glace; Enquête; Recherche; Exemple; Fabrication; Système frigorifique

1. Introduction, historical development

Food cooling with snow or ice dates back several millenniums. Especially the Romans were aware of this natural cooling method. For this purpose ice from frozen lakes or rivers and ice from glaciers was transported over long distances to populated regions for domestic applications, especially for food cooling. Some times, to further lower the temperature of the substance, salt was added to the ice or snow [1].

Nowadays artificial productions of different kinds of ice (crushed ice, flake ice, ice slurry, etc.) are performed. The ice slurry technology was invented in Russia about 80 years ago. However, the main development set in when companies in Canada [2] and Germany [3] started to manufacture ice slurry generators for commercial applications. The finer the ice particles in an ice slurry are, the better the slurries can be transported. If the ice crystals are floating in a carrier fluid, the transportation is even less energy consuming. In such cases the suspensions are named binary ice, liquid ice, ice slurry, etc. To create the ice, some water is necessary.

---

* Corresponding author. Tel.: +41-24-426-44-57; fax: +41-24-426-44-77.

E-mail address: peter.egolf@eivd.ch (P.W. Egolf).

0140-7007/$35.00 © 2004 Elsevier Ltd and IIR. All rights reserved.
doi:10.1016/j.ijrefrig.2004.07.014

Hence, ice slurries are normally ice crystals distributed in water or an aqueous solution, where different substances are added for the following purposes:

- Freezing point depression for applications below zero degrees Celsius
- Decreasing the viscosity
- Increasing the thermal conductivity of the fluid phase
- Reduction of corrosive behaviour of the ice slurry
- Prevention of agglomeration.

Ozone depletion and global warming led the refrigeration industry to consider 'old' refrigerants to be attractive again, e.g. hydrocarbons, propane, butane, ammonia, etc. because of their zero ODPs and low TEWIs [4,5]. The old substances have been used from the beginning of refrigeration technology, dating back to the middle of the nineteenth century. In the 1930s they have been replaced by new chemical compounds, namely CFCs and HCFCs. The advantage of these synthetic materials is the nontoxicity and nonflammability, the disadvantage their impact on nature. On the other hand the leakage of toxic or/and flammable 'old' refrigerants require tight systems or as an alternative a secondary circuit with a special cooling fluid for the distribution of cold. It was just this development, which is mainly responsible for the attractiveness of the ice slurry technology in our days.

At the beginning of the 1990s several research groups in industry and universities started to investigate the behaviour of ice slurries. In 1993 Snoek performed a pioneering systematic investigation of ice slurry based district cooling systems [6,7]. Active basic research on ice slurries was performed by the Danish Technological Institute in Aarhus, Denmark. Some years later the researchers of this Institute founded the 'Ice Slurry center' a large collaboration on ice slurries and ice slurry systems with numerous industrial partners. Also CEMAGREF in Antony, close to Paris, started with investigations on direct immersion of food in ice slurries and several other topics. A Swiss group launched a large European EUREKA project 'FIFE (*F*ine-crystalline *I*ce: *F*undamentals and *E*ngineering)' and started to investigate numerous fundamental and more applied problems. This group initiated an international coordination of almost all the activities on ice slurries by proposing the International Institute of Refrigeration (IIF/IIR) the foundation of a working party 'Ice Slurries'. In 1999 with the 'First Workshop on Ice Slurries'—organized by the University of Applied Sciences of Western Switzerland in Yverdon-les-Bains—a group of 30 scientific and industrial experts on ice slurries began to coordinate their work and to establish collaborations. Since then this number has increased up to seventy participants. At present they are organized, being members of the Working Party on Ice Slurries of the International Institute of Refrigeration IIF/IIR, and currently are investigating physical properties, fluid dynamic characteristics (flow patterns, flow 'phase' diagrams, pressure drops, etc.) and thermodynamic behaviour (heat conduction, heat transfer between fluids and walls for laminar and turbulent flows, etc.). An important finding was that ice slurries show a time behaviour [25] due to agglomeration of ice particles [44]. Several groups are studying buoyancy of ice crystals in the carrier fluids and stratifications in tubes and storage tanks. All these studies were published in four workshop proceedings [8].

This review is written in a popular manner for readers, not knowing ice slurries very well, but having an interest in the new technology or having decided to enter this research domain. It gives an overview without too much theoretical interpretation. On the other hand, it contains numerous valuable references for those, who want to start with an intense study of the subject. The review is split into two parts, a more fundamental section (part I) and another section describing system components and ice slurry systems (part II). Since the domain is rather new, the list of references cannot be complete, but a more comprehensive review (IIR handbook), with technical details of the subject, is under consideration. New accessible review articles are Refs. [9,44]. A special review on the development across Europe can be found in Ref. [1], where a shorter analogue review of Japanese ice slurry developments is also available [10].

2. PART I: fundamentals

2.1. Ice slurries in nature and techniques

Snow crystals mixed with water lead to a slurry, which occurs in nature and is known to everybody who was once walking in winter in rainy weather in a snowy countryside. Another kind of ice slurry is created in the growth of falling hailstones, when the heat transfer is insufficient to freeze the accreted supercooled cloud droplets. Atmospheric physicists call this form of ice slurry 'spongy ice', which was studied under laboratory conditions by List [11]. Anyway solid ice is more frequently found in nature (in glaciers, on lakes in northern areas in winter time, etc.) than ice slurries.

Supercooling is an effect, which is frequently used to also produce technical ice slurries as well. The studies of List are therefore valuable for engineers taking advantage of supercooling to produce ice slurries. The technical production of ice slurries by different physical methods are discussed in detail in Section 3.1. Many possible substances exist as additives. Very often, a 10 mass% ethanol/water solution is taken to produce ice slurries. Other additives are methanol, ethylene glycol, propylene glycol, sodium chloride, magnesium chloride, potassium chloride, etc. The corrosivity of metallic piping systems, when salts are used, must be recognized. Numerous authors present tables with comparisons of qualities of different additives [12,13], etc.

Ice slurries produced with antifreeze proteins were reported by Inada et al. [14] and Grandum et al. [15]. Antifreeze protein can be extracted from fish living in cold ambient conditions. Biological evolution led to an optimisation of these substances for similar purposes as in ice slurry systems. Inada et al. studied also the ice slurry surfaces by scanning tunnelling microscopy. Degradation of the ice surface under investigation and high costs lead to the necessity for further developing this technique, before it can be applied in technical systems.

2.2. Definitions

It is not so simple to give an exact definition of the term 'ice slurry'. Taking some risk, to our best knowledge, the following two definitions can be considered:

Definition 1. Ice slurry consists of a number of ice particles in an aqueous solution.

Definition 2. Fine-crystalline ice slurry is an ice slurry with ice particles with an average characteristic diameter, which is equal or smaller than 1 mm.

In this first step towards a definition of fine-crystalline ice slurries, the particle size probability density function is neglected. Naturally, this distribution should be narrow and at least does not show a dominance of high characteristic diameters. Anyway, these definitions give an idea, which kind of suspensions are named ice slurries, respectively fine-crystalline ice slurries. At present the most usual ice slurries, produced by mechanical scraper-type generators, have an average particle size of approximately 200 μm. All our statements in this review relate to such fine-crystalline ice slurries.

2.3. Ice particle shape and growth behaviour

Early microscopic pictures of ice slurries were published by Kauffeld et al. for an ice slurry produced with a three mass-percent $MgCl_2$ additive [12] and by Fukusako et al. for an ethylene glycol aqueous solution [16]. In his PhD work Bel classifies the ice crystals with hexagonal structure [13]. Microscopic pictures of Sari et al. show approximately ellipsoidal particles (see Fig. 1 or Ref. [17]). The different findings may be explained by the time behaviour, which was discovered by Frei and Egolf through their viscometry data [18]). DTI[1] researchers confirmed these findings and reported experimental results, which show a clear growth of the mean diameter of the ice particles as a function of time [44]. Mean diameters are calculated in different manners, and it should be carefully considered, which method is employed by the respective researcher.

For example, it is possible to determine the volume of a particle, assuming it spherical and then calculating the corresponding diameter. Okawa et al. also observed a time-behaviour during the investigations of the permeability of ice water mixtures [19]. However, in this case the particle sizes were approximately one to four millimeters before growth occurred. Further studies are necessary to definitively find the underlying physical phenomenon, which leads to the growth. The effect of this crystal growth phenomenon is that the physical properties are time dependant. Storage and mixing lead for example to a decrease of the rheological parameters (the viscosity and the critical shear stress) of up to 60%.

Fig. 1. A microscopic photograph with circa fifteen particles is shown. The dimension of the picture is 1061 μm×762 μm. The mean length of the particles evaluated from 10 such photographs is 344 μm and the standard deviation 136 μm. The mean width was determined to be 234 μm and the standard deviation 85 μm. A width to length ratio of 0.68 is therefore, calculated. The effective length was determined by a theoretical model from the projections given on the photographs.

2.4. Physical properties

To describe the density, specific enthalpy and ice mass fraction a theoretical model was developed, based on the assumption that no additive is taken up by the ice crystals during freezing [20]. Some additives, e.g. alcohols, cause an exothermic reaction when they are poured into water. This leads to a volume contraction, described by the model. Comparisons between measured and calculated densities and specific enthalpies show very good agreement. The direct measurement of the ice fraction is not so easy to perform. Sari et al. [17] roughly determined ice concentrations by statistically evaluating microscopic pictures and found results in accordance with the modelled results. Melinder published data on physical properties of numerous aqueous solutions [21]. For ice slurry applications especially the data for low concentrations are very useful. These data can be applied to extend the theoretical model to describe the behaviour of various ice slurries and those based on ethanol–water solutions. In a further article Melinder [22] also published data for ice slurry calculation and modelling, specific enthalpy charts, specific heat capacities and ice

---

[1] DTI: Danish Technological Institute in Aarhus, Denmark.

concentrations (an example is shown in Fig. 2 and further are found in his article in this special issue). A main purpose of using ice slurry is to benefit from the high latent heat or enthalpy difference at melting. The apparent specific heat capacity is simply obtained by taking the derivative of the specific enthalpy as a function of the temperature.

For systems design the rheological behaviour is also crucial. Ice slurries show Newtonian behaviour up to a threshold (critical) ice fraction and then become Non-Newtonian. Discussions on the best model approach have been performed, because a non-ideal Bingham fluid can also be successfully described by a power law model. The authors prefer the generalized Bingham model of Papanastasiou [25] to describe ice slurries with concentrations above 20% ice fraction. Ideal Bingham substances are characterized by the critical shear stress (an offset of the shear stress at zero shear velocity) and the Bingham viscosity. Non-ideal behaviour is described by a time constant. Viscosity data can be found e.g. in Refs. [23–25].

For the effective thermal conductivity several models exist; for a review see Ref. [13]. Because of the great experimental difficulty resulting from the melting phenomena, accurate measurements were not yet obtained. Special probes, based on the heat-wire method, are developed at the University of Applied Sciences of Western Switzerland to obtain reliable experimental effective thermal conductivity data.

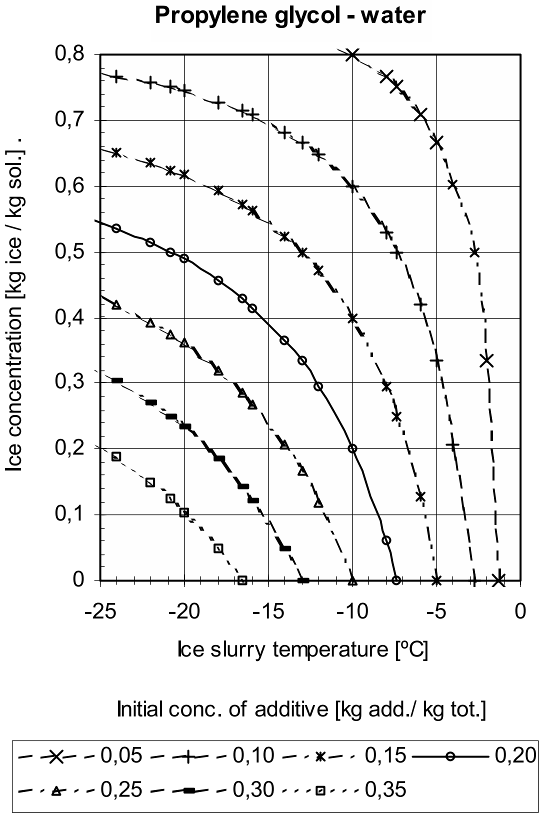

Fig. 2. Example of a chart produced by Melinder [22] to determine the ice fraction of ice slurry of propylene glycol–water with numerous ice concentrations. It can clearly be seen that the freezing point decreases for higher additive concentration.

The permeability of ice layers should also be further investigated. Some results have been obtained by Kozawa and Tanino in their study of ice water two-phase flow behaviour in ice thermal storage tanks [26]. Maximal packing factors (highest occurring ice concentrations) have not finally been investigated.

2.5. Fluid dynamics

Because of the high viscosity of ice slurries their resulting flows usually are laminar For laminar flows the theoretical models are well-known, even for some Non-Newtonian fluids, such as the Bingham fluids. A laminar Bingham fluid flowing through a cylindrical pipe shows a rectangular plug in its velocity profile. At the sides, the plug (which is symmetric to the pipe axis), has two parabolic wings (Fig. 3). When the ice fraction decreases, this plug width decreases linear with the critical shear stress. When it vanishes, the two parabolas merge together and yield the well-known parabolic Hagen Poiseuille profile of laminar Newtonian flow through a pipe. Sari et al. [17] have managed to measure the plug profile with a new measuring technique, the ultrasound velocity profiler. In Fig. 3 it is compared with the analytical solution, obtained with the Bingham flow theory (from Ref. [27]). These considerations are only valid when the ice particles are homogeneously distributed. However, especially at low velocities, the ice particles rise by buoyancy to the top of the tube and

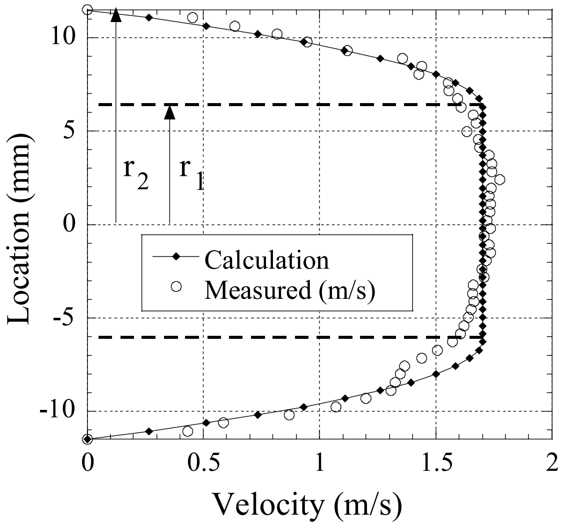

Fig. 3. Measured and calculated velocity profiles compared with each other for a mass concentration of 11% ethanol–water solution and an ice fraction of 16%. A plug and two parabolas at its sides are observed.

stratification (a non-uniform ice concentration profile) occurs. Studies of the different types of flows and the corresponding flow ‘phase’ diagrams were performed by Kitanovski and Poredos [28]. Such diagrams are very difficult to determine. Their boundaries may show fractal behaviour.

Free convection flows in tanks have been studied theoretically by Egolf et al. [29], applying multi-component fluid dynamics, and experimentally by Vuarnoz et al. [30].

The experimental determination of Nusselt relations for the calculation of heat transfer coefficients initially led to large deviations in the results obtained by different groups. At that time, the time behaviour of ice slurry was not yet discovered. Today the results are comparable and show high heat transfer coefficients, approximately 3000 W/m^2 K for laminar and 4500 W/m^2 K for turbulent flows [12,31]. For forced convection they depended on the Prandtl number, the Reynolds number and the Hedström number. The Hedström number contains the critical shear stress and it is a measure for the Bingham effect. Kawanami et al. [32] have investigated heat transfer in bendings of rectangular ducts.

One has to be aware that very often heat exchangers are used, where the secondary fluid is air. The resistance of air is more than two orders of magnitude higher than that of the ice slurry on the other side of the heat-transferring wall. Hence, the resistance on the ice slurry side is not so important. It is very often negligible in the calculation of the overall heat transfer coefficient.

Heat transfer measurements with plate heat exchangers were performed by Stamatiou et al. [33] and Bellas [34].

Sari et al. [31] found that in laminar flow the heat transfer to the ice slurry in a tube results mainly in heating a small thermal boundary layer, because of the low thermal diffusivity. Some estimates with a gradient-type turbulence model were performed for turbulent flow. This finding leads to the conclusion that placing of small mixing elements in tubes could be advantageous.

3. Part II: systems and practical applications

3.1. Ice slurry generators

Numerous research studies are concentrated on the components of ice slurry systems For example different kinds of ice slurry generators exist:

- Mechanical-scraper type with:
  - rotating knifes (Fig. 4a) or scrape blades
  - rotating cylindrical slabs (Fig. 4b)
  - rotating brushes
  - screws
- Vortex-flow type
- Direct-injection or direct heat exchange type
- Fluidized-bed ice generator

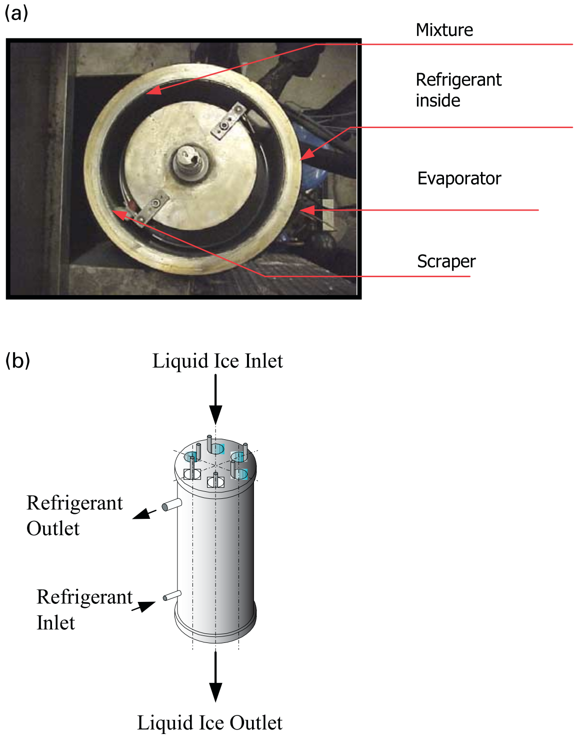

Fig. 4. (a) An ice slurry generator of mechanical-scraper type is shown (from Ref. [1]). (b) A rotating slab generator allows a higher ice production power to volume ratio.

- Ice generators using supercooled water with different types of nucleation initialization:
  - by a momentum decrease (flow perpendicular towards a cold wall)
  - by an ultrasonic field
  - by bubble nucleation.
- Ice slurry generators with specialized ice nucleating and ice repelling surfaces.

In the typical mechanical-scraper type ice slurry generator the refrigerant evaporates in a double-wall cylinder. Through the inside space, bounded by the inner cylinder, the water or aqueous solution flows. Here ice crystals are created. The ice crystals are removed from the wall by rotating scrapers (knifes). The crystals then fall into the suspension and accumulate; i.e. the ice fraction increases. The generator with rotating slabs has a large surface for the ice crystal creation per volume of ice slurry generator. This type is therefore used when higher ice production rates are required. Instead of metallic scrapers polymer brushes can also be applied.

In other types of ice slurry generators the crystals are produced in tubes and removed by turning screws.

In the vortex-flow generator a turbulent flow is produced. The wall of the ice generator has a special coating, so that the ice crystals can be more easily removed from the surface by the turbulent eddies in the flow. The eddy sizes created should be adapted to the crystal size. It is assumed, but not confirmed, that resonant conditions yield the most powerful removing effect.

A direct contact heat exchanger ice slurry generator was built and investigated by Chuard and Fortuin [35]. Basic investigations of this principle were performed at ILK in Dresden [36]. In this type of ice slurry generators, the refrigerant is directly injected into the water domain. Liquid droplets of refrigerant enter through nozzles, normally at the bottom of the generator, and start to evaporate. The growing droplet/bubbles also named drobbels, by buoyancy rise to the top of the water-containing column. The evaporated refrigerant is collected above the water surface, dried and pumped back into the compressor to be compressed and prepared for a second cycle of expansion and cooling of the water column. The droplets in the water show coalescence, break-up by a shaking in the turbulence field and buoyancy by the density difference between the gas and liquid phase. At present a group working with the first author of this article investigates experimentally and simulates numerically the multi-component and multi-phase flows in direct-contact heat exchangers by applying computational fluid dynamics.

The fluidized bed ice slurry generator works very similarly to the mechanical scraper type. The main difference is that now a fluidized bed is created in the main tube, containing a large number of steel or glass particles. These particles are spread in the inner space by a turbulent upward flowing liquid, removing the ice crystals from the wall by hitting and breaking them away. In this continuous process, a clean surface with a high heat transfer rate is obtained. Meewise and Infante Ferreira [37] studied experimentally and theoretically fluidized-bed ice generators.

Ice slurry generators exist, which use supercooled water for the production of ice slurry. The initiation of the freezing must be absolutely controllable. If freezing occurs too early, the system blocks. Nucleation may be obtained by a flow, which is directed perpendicularly toward a cold wall. Japanese researchers are testing nucleation initiated by ultrasonic beams [38]. Because these types of generators produce ice slurry of low ice fraction, ice concentrators must be applied [12]. They usually contain a sieve through which the liquid is removed by a pump. The remaining suspension has then a higher ice fraction. The difference in density between the fluid and the solid phases can be used for separation by centrifugal techniques.

At present several types of ice slurry generators exist. Those which are applicable in practice and guarantee a continuous operation without problems are still too expensive. This is a serious problem for the further development of the technology. It is therefore extremely valuable that numerous new types of ice generators are now investigated in research institutes and industrial research and development laboratories.

3.2. Storage and mixing

To shift peak loads in electricity supply the high cold accumulation potential of ice slurries can be taken advantage of. Such an ice slurry system must then contain a storage tank. If the ice slurry in the tank is homogeneously stirred, the probability of an unproblematic operation of the system is much higher. On the other hand, the mixing of the ice slurry can be very energy consuming. Meili et al. [39] have shown that an intermittent operation of mixing is possible, e.g. by turning the mixer off during the night. In Japan large systems, such as the Kyoto station building, are operated with huge storage tanks with pure water ice slurry and no mixing. In such systems mostly cold water is removed from the storage tank to be used for air-conditioning purposes.

A possibility was launched to eliminate mixing and to still guarantee a well-defined ice fraction in the supply tubes of an ice slurry system. The ice slurry in the tank undergoes full stratification by buoyancy of the ice particles, because no mixing is applied. A fraction of ice is lifted above the free liquid surface. By an Archimedes screw high-ice-fraction, slurry is transported out of the tank and mixed with very low ice-fraction slurry from the lowest region in the tank. The controlled (or regulated) mixing process guarantees a stable pre-defined ice fraction.

Experimental work and theoretical calculations are both important when investigating free convection flows in storage tanks. Furthermore, Hong et al. [40] have performed computational fluid dynamic studies on the mechanical-scraper ice slurry generator and also on flows in storage tanks with running mixing devices.

3.3. Pumps and piping

At ice fractions below 15–20% the suspensions usually show Newtonian behaviour. In this regime, centrifugal pumps can be operated without difficulties. However, these pumps are not designed for higher ice fractions. Their efficiency decreases with increasing ice fraction. For the domain of high ice fractions, displacement pumps should be chosen. A broad characterization of different pump types, operating with ice slurries, was published by Frei and Huber [41], who measured pump characteristics of a centrifugal pump, a side-channel pump, and a screw pump. Not much is known so far about erosion effects in pumps for long-time operation modes.

Piping systems may be installed as it has been done for years in other systems with secondary refrigerants. If salts are used as additives, attention must be paid to the corrosivity of the substances in metal tubes. Plastic tubes may be used to connect the components of ice slurry systems. Many practical advices (Fig. 5) for the design and operation of ice slurry systems were published by Schmidt, who built systems in Germany and Austria and gained much practical experience [42].

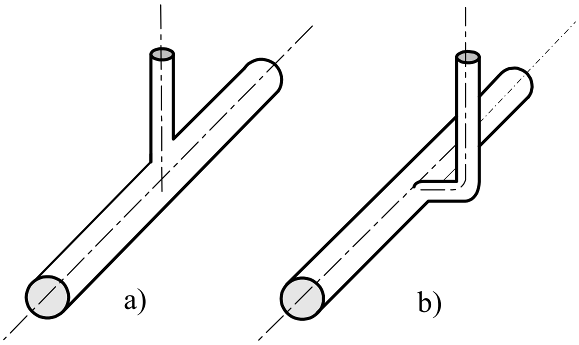

Fig. 5. Two branchings in an ice slurry system to a higher floor in a building. It should not be constructed as shown in (a). A better solution is shown in (b). If vertical ice particle stratification occurs, in case (b) the two branches will obtain more equal ice fractions. Furthermore, the radii of bendings should not be chosen too small, such as in (b).

3.4. Consumers

Consumer is the name chosen for equipment, which uses cold energy for cooling purposes It 'consumes' heat of a heat source by a melting ice slurry.

In usual refrigeration applications, e.g. supermarkets, a display cabinet is a consumer. Until present, display cabinets were used, which were designed for conventional brine systems. For ice slurries heat exchangers can be designed a little smaller. Furthermore, in many cases, when using ice slurry, electric defrosting is not necessary anymore. The reason is that a high cooling power (capacity) can be obtained with low temperature differences, i.e. a higher secondary coolant temperature. This reduces investment and system operation costs [43].

In process applications the consumers are special devices, machines, reactors, etc. For example, in plastics production the uniform temperature field distributions of phase-change slurries yield a higher quality of the products and a smaller number of waste objects per unit time.

3.5. Systems in practice

In Section 3.4 first application areas of the ice slurry technology are outlined. A further application is the milk production, where very high peak loads are to be covered. Because of the large number of ice particles, ice slurries possess a high heat transfer surface per unit volume. In a short time a large number of ice crystals can be melted. This technology is therefore very advantageous for extremely high peak-load demands. Ice slurry systems also have a great potential for applications in buildings and special technologies like aircraft cooling, particle detector cooling, etc. For safety reasons, other phase change slurries (PCS) may yield a better solution in the last application. If an accident occurs, ice slurry in a high-energy physics field evaporates and produces hydrogen with a resulting danger for an explosion. PCS substances with higher melting temperatures could also be used for cooling of concentrated solar collectors, fuel cells, etc.

An ideal and not too expensive ice slurry system could contain a direct-contact heat exchange ice slurry generator, which is connected to a storage tank without a conventional mixing device (see Section 3.2) and a monotube distribution system for the transport of cold. For monotube systems the approximately constant temperature of ice slurries over the entire operation range of the system is a great advantage.

At present reliable ice slurry systems can be built, but they should further be optimized concerning their energy demand. The costs for construction of ice slurry systems are still quite high.

In a review article of Egolf and Kitanovski [45] existing systems in practice are described and numerous references are given. Especially in Japan and Korea, several large-scale applications of the ice slurry technology have been realized. In European countries close to the sea, several applications in fishing industry are found. A Handbook on Ice Slurries—which will be published by the International Institute of Refrigeration—is in its final production stage. It will outline all the topics of this special issue in more detail and it will contain an extensive list of existing systems in practice.

4. Conclusions

The industrial use of ice slurry has just begun (about 30 years ago). Ice slurry has a great potential for the future. The use of ice slurry enables the use of indirect refrigeration systems with small charge of the primary refrigerant as well as the possibility of ice storage and money savings associated with that. Furthermore, the use of ice slurry gives the possibility of direct contact cooling and freezing of products.

Ice slurry has better transport properties in tubes and heat exchangers, i.e. an approximately eight times higher heat capacity of ice slurry than of traditional single-phase secondary refrigerant is observed. The tube diameter can therefore be reduced by about 50% and the velocity inside the tubes can also be reduced to a half. The energy consumption of the pumps to transport the ice slurry is only about one eights of the energy consumption necessary in traditional single-phase secondary refrigerant systems. The heat transfer coefficient for ice slurries is at moderate heat fluxes increased by a factor of 50–100% compared to conventional secondary refrigerants. Therefore, ice slurry is believed to be a very vigorous future (secondary) refrigerant.

The authors apologize to all researchers, who made important contributions to the development of the ice slurry technology in its initial period, but have not been cited. Such a review article always reflects personal views and preferences, as regards to experiment, theory, and practical applications. The leading functions of the authors in the IIR

Working Party on Ice Slurries of the International Institute of Refrigeration led to a prevailing citation rate of articles published by this organization.

Acknowledgements

The first author is grateful to the European Commission and the 'Bundesamt für Bildung und Wissenschaft' for funding project ENK6-CT-2001-00507, PAMELA. Furthermore he and his researchers thank the 'Gebert Rüf Stiftung (GRS)', and the 'Haute Ecole de Suisse Occidentale (Hes-so)' for funding projects on ice slurries. The second authors work was funded by the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ASHRAE), by the Danish Energy Agency, the Danish Environmental Protection Agency and the Danish Ministry for Trade and Industry. The support of all funding companies and organizations is highly appreciated, also those not mentioned here. Furthermore, the authors are grateful to Kostadin Fiikin for helpful remarks.

References

[1] T.M. Hansen, M. Kauffeld, O. Sari, P.W. Egolf, F. Pasche. Research, development and applications of ice slurry in Europe, from ancient Rome to modern technology. Proceedings of the Fourth Workshop on Ice Slurries of the International Institute of Refrigeration, Osaka, Japan; 12–13 November 2001. p. 1–12.

[2] M. Kawaji, E. Stamatiou, R. Hong, J.J. Xu, D.J. Shang, V. Goldstein. Experimental and numerical investigations of ice-slurry generator performance. Proceedings of the Second Workshop on Ice Slurries of the International Institute of Refrigeration, Paris, France; 25–26 May 2000. p. 92–100.

[3] J. Paul. Binary ice—technologies for the production of pumpable ice slurries. Proceedings of the International Institute of Refrigeration; 1992. p. 5-1–5-10.

[4] Series on 'Informatory notes on refrigerants'. International Institute of Refrigeration, Paris; 1987–2000.

[5] J. Stene. Guidelines for design and operation of compression heat pump, air conditioning and refrigerating systems with natural working fluids. Final Report of the International Energy Agency, Annex 22. Compression systems with natural working fluids, Report No. HPP-AN22-4; 1998.

[6] C.W. Snoek, The design and operation of ice-slurry based district cooling systems. IEA report: district heating, The Netherlands Publishers, Novem BV, 1993.

[7] C.W. Snoek, S. Walosik, Ice slurry transport for district cooling networks, 12th Int Conf Slurry Handling 12 (1993) 511–523.

[8] Proceedings of the Workshops on Ice Slurry of the International Institute of Refrigeration, Available at the IIR headquarters, see www.iifiir.org.

[9] V. Ayel, O. Lottin, H. Peerhossaini, Rheology, flow behaviour and heat transfer of ice slurries: a review of the state of the art, Int J Ref 1 (2003) 95–107.

[10] H. Inaba. Fundamental research and development of ice slurry for its cooling system design in Japan. Proceedings of the Fourth Workshop on Ice Slurries of the International Institute of Refrigeration, Osaka, Japan; 12–13 November 2001. p. 13–14.

[11] R. List. Atmospheric formation of spongy ice. Proceedings of the First Workshop on Ice Slurries of the International Institute of Refrigeration, Yverdon-les-Bains, Switzerland; 27–28 May 1999. p. 10–17.

[12] M. Kauffeld, K.G. Christensen, S. Lund, T.M. Hansen: Experience with ice slurry. Proceedings of the First Workshop on Ice Slurries of the International Institute of Refrigeration, Yverdon-les-Bains, Switzerland; 27–28, May 1999. p. 42–73.

[13] O. Bel. Contribution à l'étude du comportement thermo-hydraulique d'un mélange diphasique dans une boucle frigorifique a stockage d'énergie. PhD Thesis, No. 96 ISAL 0088, L' Institute National des Sciences Appliquées de Lyon, France; 1996.

[14] T. Inada, S.S. Lu, S. Grandum, A. Yabe, X. Zhang. Microscale analysis of effective additives for inhibiting recrystallization in ice slurries. Second Workshop on Ice Slurries of the International Institute of Refrigeration, Paris, France; 25–26 May 2000. p. 84–91.

[15] S. Grandum, A. Yabe, K. Nakagomi, M. Tanaka, F. Takemura, Y. Kobayashi, M. Ikemoto, E.P. Frivik, Investigation of the characteristics of ice slurry containing antifrezze protein for ice storage, Trans Jpn Soc Mech Engrs 63/609 (1997) 1770–1776.

[16] S. Fukusako, Y. Kozawa, M. Yamada, M. Tanino. Research and development activities on ice slurries in Japan. Proceedings of the First Workshop on Ice Slurries of the International Institute of Refrigeration, Yverdon-les-Bains, Switzerland; 27–28 May 1999. p. 83–105.

[17] O. Sari, D. Vuarnoz, F. Meili, P.W. Egolf. Visualization of ice slurries and ice slurry flows. Proceedings of the Second Workshop on Ice Slurries of the International Institute of Refrigeration, Paris, France; 25–26 May 2000. p. 68–81.

[18] B. Frei, P.W. Egolf. Viscometry applied to the Bingham substance ice slurry. Proceedings of the Second Workshop on Ice Slurries of the International Institute of Refrigeration, Paris, France; 25–26 May 2000. p. 48–60.

[19] S. Okawa, A. Saito, T. Hozumi, H. Kumano. Effect of ice/water storage on the permeability of the mixtures. Proceedings of the International Conference on Fundamental Research on Thermal Energy Storage to Preserve Environment; January 11 2002. p. 49–54.

[20] P.W. Egolf, B. Frei. The continuous-properties model for melting and freezing applied to fine-crystalline ice slurries. Proceedings of the First Workshop on Ice Slurries of the International Institute of Refrigeration, Yverdon-les-Bains, Switzerland; 12–13 November 2001. p. 25–40.

[21] A. Melinder. Acurrate thermophysical property values of water solutions are important for ice slurry modelling and calculations. Proceedings of the Third Workshop on Ice Slurries of the International Institute of Refrigeration, Horw/Lucerne, Switzerland; 16–18 May 2001. p. 11–18.

[22] A. Melinder. Using property values of water solutions and ice to estimate ice concentration and enthalpy values of ice slurries. Proceedings of the Third Workshop on Ice Slurries of the International Institute of Refrigeration, Horw/Lucerne, Switzerland; 16–18 May 2001. p. 19–26.

[23] J. Guilpart, L. Fournaison, M.A. Ben Lakhdar, D. Flick, A. Lallemand. Experimental study and calculation method of transport characteristics of ice slurries. Proceedings of the First Workshop on Ice Slurries of the International Institute of Refrigeration, Yverdon-les-Bains, Switzerland; 27–28 May 1999. p. 74–82.

[24] T.M. Hansen, M. Kauffeld, K. Grosser, R. Zimmermann. Viscosity of ice slurry. Proceedings of the Second Workshop on Ice Slurries of the International Institute of Refrigeration, Paris, France; 25–26 May 2000. p. 38–45.

[25] B. Frei, P.W. Egolf. Viscometry applied to the Bingham substance ice slurry. Proceedings of the Second Workshop on Ice Slurries of the International Institute of Refrigeration, Paris, France, 25–26 May 2000. p. 48–60.

[26] Y. Kozawa, M. Tanino. Ice-water two-phase flow behaviour in ice heat storage systems. Proceedings of the First Workshop on Ice Slurries of the International Institute of Refrigeration, Yverdon-les-Bains, Switzerland; 27–28 May 1999. p. 147–157.

[27] E.J. Wasp, J.P. Kenny, R.L. Gandhi, Solid–liquid flow slurry pipeline transport, Series Bulk Mater Handling 1 (4) (1975).

[28] A. Kitanovski, A. Poredos, Concentration distribution and viscosity of ice-slurry in heterogeneous flow, Int J Refr 25 (6) (2002) 827–835.

[29] P.W. Egolf, D. Vuarnoz, O. Sari. A model to calculate dynamical and steady-state behaviour of ice particles in ice slurry storage tanks, Proceedings of the Fourth Workshop on Ice Slurries of the International Institute of Refrigeration, Osaka, Japan; 12–13 November 2001. p. 25–39.

[30] D. Vuarnoz, O. Sari, P.W. Egolf. Correlations between temperature and particle size distributions of ice slurry in a storage tank. Proceedings of the Fourth Workshop on Ice Slurries of the International Institute of Refrigeration, Osaka, Japan; 12–13 November 2001. p. 123–134.

[31] O. Sari, F. Meili, D. Vuarnoz, P.W. Egolf. Thermodynamics of moving and melting ice slurries. Proceedings of the Second Workshop on Ice Slurries of the International Institute of Refrigeration, Paris, France, 25–26 May 2000. p. 140–153.

[32] T. Kawanami, M. Yamada, S. Fukusako. Melting characteristics of fine particle ice slurry at the return bend of flow path. Proceedings of the Third Workshop on Ice Slurries of the International Institute of Refrigeration, Horw/Lucerne, Switzerland; 16–18 May 2001. p. 69–75.

[33] E. Stamatiou, M. Kawaji, B. Lee, V. Goldstein. Experimental investigations of ice-slurry flow and heat transfer in a plate-type heat exchanger. Proceedings of the Third Workshop on Ice Slurries of the International Institute of Refrigeration, Horw/Lucerne, Switzerland; 16–18 May 2001. p. 61–68.

[34] J. Bellas, I. Chaer, S.A. Tassou, Heat transfer and pressure drop of ice slurries in plate heat exchangers, Int J Appl Therm Eng 22 (7) (2002) 721–732.

[35] M. Chuard, J.P. Fortuin. COLDECO—a new technology system for production and storage of ice. Proceedings of the First Workshop on Ice Slurries of the International Institute of Refrigeration, Yverdon-les-Bains, Switzerland; 27–28 May 1999. p. 140–146.

[36] E. Wobst, D. Vollmer. Ice slurry generation by direct evaporation of refrigerant. Proceedings of the First Workshop on Ice Slurries of the International Institute of Refrigeration, Yverdon-les-Bains, Switzerland; 27–28 May 1999. p. 126–132.

[37] J.W. Meewise, C.A. Infante Ferreira. Ice slurry production with a fluidised bed heat exchanger. Proceedings of the Second Workshop on Ice Slurries of the International Institute of Refrigeration, Paris, France; 25–26 May 2000. p. 101–108.

[38] M. Tanino, Y. Kozawa, D. Mito, T. Inada. Development of active control method for supercooling releasing of water. Proceedings of the Second Workshop on Ice Slurries of the International Institute of Refrigeration, Paris, France; 25–26 May 2000. p. 127–139.

[39] F. Meili, O. Sari, D. Vuarnoz, P.W. Egolf. Storage and mixing of ice slurries in tanks. Proceedings of the Third Workshop on Ice Slurries of the International Institute of Refrigeration, Horw/Lucerne, Switzerland; 16–18 May 2001. p. 97–104.

[40] R. Hong, M. Kawaji, V. Goldstein. Numerical investigation of ice-slurry flow and heat transfer in a scraped ice generator and storage tank. Proceedings of the Third Workshop on Ice Slurries of the International Institute of Refrigeration, Horw/Lucerne, Switzerland; 16–18 May 2001. p. 119–125.

[41] B. Frei, H. Huber. Characteristics of different pump types operating with ice slurry. Proceedings of the Third Workshop on Ice Slurries of the International Institute of Refrigeration, Horw/Lucerne, Switzerland; 16–18 May 2001. p. 137–144.

[42] G.H. Schmidt. Design experience with FLO-ICE® and binary ice as a secondary refrigerant for refrigeration installations. Proceedings of the First Workshop on Ice Slurries of the International Institute of Refrigeration, Yverdon-les-Bains, Switzerland; 27–28 May 1999. p. 133–139.

[43] L. End, H. Eicher, P.W. Egolf. Ice slurry pilot and demonstration system for food refrigeration in supermarkets. Proceedings of the Third Workshop on Ice Slurries of the International Institute of Refrigeration, Horw/Lucerne, Switzerland; 16–18 May 2001. p. 155–62.

[44] T.M. Hansen, M. Radosevic, M. Kauffeld. Behaviour of ice slurry in thermal storage. ASHRAE research project RP 1166. Final Report; February 2002.

[45] P.W. Egolf, A. Kitanovski. A review on the phase change slurry technology and some large-scale applications in buildings and industry. Proceedings of the Seventh Expert Meeting of the Slovenian District Energy Association, SDDE, Portoroz, Slovenia; 15–16 March, 2004. p. 27–43.