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From physical properties of ice slurries to industrial ice slurry applications

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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.

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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