ABSTRACT
Most people working in the field of liquid/solid two-phase secondary refrigerants in general and ice slurries in particular are convinced that this solution is an alternative to systems using single-phase secondary fluids, and that it can also be a suitable option when replacing direct-expansion systems. Indeed, the numerous benefits of ice slurries are well known [1]: reduction in direct and indirect greenhouse gas effects, reduction in and containment of the refrigerant charges, reduction in the size of the refrigeration plants thanks to thermal storage, distribution networks with smaller pipe diameters, optimal energy management, and enhanced cooling effect. So what is holding back the development of ice slurries?

This article describes various issues and reports on a few comments received from various countries. Its aim is to open discussion, hoping that other answers will be provided: some of these answers are already emerging and were presented during the 7th Conference on Phase Change Materials and Slurries in Dinan, France, on September 13-15, 2006. Recent achievements in Austria, France and Japan (in the air-conditioning field) are mentioned at the end of this article in order to illustrate recent developments in this technology.

Keywords — ice slurry, secondary refrigerants, thermal storage, energy efficiency

1 INTRODUCTION
In the early 1990s, evaporators for the generation of two-phase liquid/solid secondary refrigerants for use in direct and indirect cooling, through the generation of ice crystals from an aqueous alcohol or sodium chloride solution, started emerging in discussions. Similar exchangers had already been used in order to concentrate wines by freezing part of the water and also to cool down the mixes for ice creams or creamy products such as sauces.

The direct cooling of water (with the addition of a small amount of salt) below its freezing point was developed in order to cool fish rapidly, on board trawlers or on land, but the freezing capacities required in these applications are limited. Double-tube scraped type exchangers are used for this application.

In 1995, the first indirect-cooling plant for a supermarket was implemented in France for display cabinets used for perishable products such as meat. At the same time, other retail systems were launched in Switzerland and The Netherlands. The main benefits of ice slurry technology were confirmed and a new era for indirect refrigeration appeared to be dawning. More than 10 years later, this revolution has yet to come about. What are the causes and explanations for such sluggish expansion?

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2 SITUATION

In order to explore the possible explanations, the various arguments in favour of ice slurries should be kept in mind so as to clearly grasp their particular importance. The following only concerns use in indirect cooling.

2.1 Reduction in refrigerant charges and containment within machine rooms

Use of an indirect system makes it possible to reduce the refrigerant charge by 70-80%; the direct greenhouse effect is thus about 8-10 times lower than that of a direct expansion system using an HFC refrigerant as primary fluid. When a plant uses an ice slurry instead of a single-phase secondary refrigerant, an additional 10% reduction in the greenhouse effect can be obtained with a lower refrigeration capacity.

2.2 Direct cooling, and therefore the use of ice slurries, makes it possible to use certain natural refrigerants such as ammonia or hydrocarbons

These refrigerants have little or no global warming potential.

2.3 Thermal storage makes it possible to reduce the size of plants by 15–30% and to avoid peak periods

The energy absorbed is in theory directly related to daily cooling needs. Thermal storage makes it possible to avoid running the compressor under part-load conditions which lead to reduced performance, above all where screw compressors equipped with sliding regulating systems are used. Moreover, the pumping energy required is lower (lower volume rate).

The size of the compressors and transformer are reduced to the same extent, as is the electrical power required. The latter can prove to be important (and this is already the case in some countries) where production and distribution networks are limited.

Reducing the size of a refrigerating plant by 15-30% significantly lowers investments; the savings achieved can be used to finance the additional costs incurred by the installation of the thermal-storage system.

2.4 The energy efficiency of an ice-slurry plant is greater than that of a plant using a liquid single-phase secondary refrigerant

This enhanced efficiency is due to several factors: a small temperature difference at the level of the secondary refrigerant, smaller pumps and enhanced heat transfer.

It can also be emphasised that the performance of direct expansion systems is lower because such systems have less efficient evaporators (superheating and frost formation are among the problems encountered) and in addition the compressors used have lower coefficients of performance (COPs) because of pressure drops and superheating in the suction lines.

The thermal storage system makes it possible to markedly enhance the efficiency of the plant where the plant is operated only when the outside conditions are favourable (preferably at night and not when the outside temperature is high).

This system also makes it possible to benefit from lower kWh power tariffs (for instance night tariffs) and thus to reduce the energy bill.

2.5 The high latent heat of ice slurry makes it possible to reduce the cross-section of distribution networks fourfold to fivefold

With a 25% crystal concentration, the thermal capacity of ice slurry is approximately four times higher than that of a single-phase liquid refrigerant subjected to a temperature rise of 5°C and five times that of such a refrigerant subjected to a temperature rise of 4°C. The price of the distribution networks, which is one of the main sources of additional costs for indirect refrigerating equipment compared with direct-expansion equipment, is thus significantly reduced (tubes, pumps, control valves, insulation, labour costs and secondary refrigerant).

Since the IIR Working Party on Ice Slurries first met in Yverdon-les-Bains, Switzerland, on May 27-28, 1999, numerous ice slurry production systems have been presented and tested (above all in research laboratories) but until now no real breakthroughs have been.
achieved, with the exception perhaps of the supercooling technology used in Japan where numerous 700–4000 kW [2] plants have been implemented in air conditioning applications. In these systems, the liquid ice is produced and stored but not supplied to the terminal units, probably because of the complexity of the distribution (risk of crystal build-up, difficulty for the users to control the crystal concentration at the level of the terminals).

As the initial temperature of secondary refrigerants is around 0°C, however, instead of 6–8°C in a conventional chilled water system, the diameter of the piping in the distribution networks is halved. Another important feature is the smaller air ducts; a lower secondary refrigerant entry temperature in the air cooling coils makes it possible to cool it to a lower temperature, thus reducing the airflow and thus the duct section. The air is then mixed with recycled air, thanks to induction for example, during blowing in buildings, to ensure that the air is not too cold. These two aspects are particularly important, whether in financial terms or in terms of size and because of the possibility of using very different cooling loads during different diurnal or night periods and when the cost of the kWh is high. All these reasons justify the use of ice slurries, even when the latter are not distributed to terminals.

In Europe, scraped-surface exchangers are the most widely used (double-tube or shell-and-tube systems with orbital rods) and a small number of brushed-surface disk exchangers have been used in a limited number of plants (5-10 in a few countries) for capacities of 10-100 kW, with a few exceptions for which systems with capacities of 250-800 kW are employed. Several large installations with vacuum slurry production using water as a refrigerant should also be mentioned and so should the “triple point” concept that is applied in South African mines [3]. As in the case of Japan, reducing the size of pumps, piping and air ducts is a very important factor in mines.

Several sites with numerous scraped-surface double-tube exchangers, used in large numbers because of their limited capacity, have been implemented to air conditioned buildings, in Korea for example.

As indicated above, applications for direct cooling, mainly for fish (on board trawlers or on land) and certain vegetables are not covered in this article. Installed capacities vary from 5-100 kW.

**ABOUT THE AUTHOR**

Paul Rivet was born in 1946 and graduated from the Institut Français du Froid Industriel (IFFI) in 1965.

He joined the research department of Chantiers de l’Atlantique in 1967, then became sales engineer with Escher-Wyss/Sulzer before being appointed Director of the refrigeration division of Alfa-Laval then Stal-Refrigeration.

After having been Director of Cryokit in 1989, he joined MC International (formerly Johnson Controls) as Director of Industrial Refrigeration. Member of Commission B2 of the IIR and member of the IIR Working Party on Ice Slurries (now the IIR Working Party on Phase-Change Materials and Slurries for Refrigeration and Air Conditioning), he has also been a lecturer at IFFI since 1990 and is on the Board of the French Refrigeration Association [Association Française du Froid, AFF].

He is also president of the committee handling the joint commemoration of the IIR’s and AFF’s centenaries in 2008. Paul Rivet has extensive experience in the field of industrial refrigeration processes and has written many papers presented at IIR conferences and congresses.
and are provided by complete units with parallel scraped-surface double-tube exchangers.

3 WHAT IS HAMPERING DEVELOPMENT?

3.1 Unitary capacity

In order to meet indirect cooling needs in the food industry and industrial plants, generators should have a capacity of 250–500 kW which is not the case at the time of writing. In order to achieve 800 kW, three to eight “mechanical” generators are necessary and the investment cost of the overall system (generators plus pumps plus the plant) goes beyond an economically acceptable level.

The solution probably lies in the use of “flexible surface” systems such as plate exchangers with no scraping or only a small amount of brushing, or in the use of immiscible fluids making it possible to employ standard liquid chillers.

Such solutions are being investigated or are in an industrial experimental phase.

3.2 The price of generators

Mechanical generators are not yet sufficiently competitive. This is not simply due to the low production volume. Instead, it is above all related to the fact that double-tube generators involve difficult pressure management and are more expensive to manufacture: moreover, the price of these systems rises considerably as the diameter and the length of the tubes increase. As indicated in section 3.1 above, the alternative solutions mentioned can lead to cuts in the manufacturing cost per kW and can reduce the number of generators required.

3.3 Reliability and maintenance costs

The first systems (double-tube generators) launched around 1995 are still in operation in indirect refrigerating circuits. Maintenance costs, confirmed by users who mention problems encountered with the replacement of generators and bearings, and problems with the surface treatment, are too expensive. These are probably mere teething problems, but they have hampered the application of this technology in certain countries for several years.

3.4 The cost of thermal-storage systems

Thermal storage is a necessity if latent heat is to be used optimally, but its impact on investment is important and often difficult to offset by cutting costs at the level of circuits and compressors. The cost of the thermal storage system does not solely comprise that of the storage tank, but also encompasses that of the liquid contained in it, the size of the plant, thermal insulation and pumping systems.

3.5 Performance

Even when pumping, scraping and brushing capacities are low, users report low performance: capacities are not achieved or the evaporation temperature is lower than expected. Such reduced performance can be explained by the following: tests are essentially carried out in laboratories, feedback from monitored sites is very scarce, knowledge is limited by the small numbers of plants, supply of direct-expansion generators tends to be sub-optimal, scraping or brushing tends to be insufficiently effective to obtain optimal heat exchange and the presence of excess oil also plays a role.

When producing ice slurries, however, it is crucial to operate with high evaporation temperatures in order to benefit from the very small temperature difference at the level of the secondary refrigerant along with enhanced exchange coefficients in order to compete with direct expansion systems.

3.6 Investment and return on investments

Today, the total investment cost is now higher than that of a direct-expansion system because of the generators, pumps, circuits, storage, and also because of the limited number of systems implemented. This additional cost is not offset by cost cuts linked to the reduced capacities of the compressors.

On the other hand, the price of electricity per kWh, in France for instance, is low, especially in summer when demand is high. This is changing not only in France but also in many other European countries. Environmental pressure and regulations on CO2 emissions have driven the need to reduce power consumption. This is undoubtedly an incentive for the development of ice slurries. Energy savings and,
consequently, the expected system performance, are a key factor.

Implementation of a single tariff, which is likely to take place, will no longer make it possible to promote production during off-peak periods during which the kWh is less expensive, this being the case today.

The return on investment is clearly far longer than the two to three years considered as acceptable by many customers, especially in the distribution sector. Governmental subsidies are necessary, at least during the launching period. The setting up of energy savings certificates can act as an incentive.

3.7 Other points

The following are worth mentioning:

• It is difficult to obtain the charge curve that makes it possible to optimise storage capacity and hence investment. Measurements and calculations that make it possible to obtain this curve do exist.

• It is difficult to render stored capacity when desired and at the levels required; this problem can be solved thanks to additional studies and tests.

• Many ice-slurry production systems have been developed over the years, but only a few are in fact being applied.

• Communication is insufficient: articles, calculations, pay-back periods and users’ experiences need to be publicised.

• Environmental awareness is insufficient, but is currently gaining ground.

4 CONCLUSION

The various IIR conferences, the work of many inventors, researchers, manufacturers and installers working on ice slurries for over 10 years, backed up by the need to address environmental and energy-related issues must stimulate progress in this technology. Ice slurry is attracting growing interest, as demonstrated by the number of plants implemented recently [4] and the emergence of promising new production technology such as that presented during the 7th Conference on Phase-Change Materials and Slurries held in Dinan, France [5].

This article should not be construed as painting a negative portrait: the author has been working on ice slurries for over a decade and remains convinced that two-phase secondary refrigerants in general and ice slurries in particular are highly useful. These refrigerants address the challenges currently faced by the refrigeration and air conditioning sector, thanks to solid-phase latent heat, better energy efficiency, reduced size, refrigerant containment and to the fact that it is possible to use natural environmentally friendly refrigerants.

We now appear to have gone beyond the experimental stage and the teething problems would now appear to be a thing of the past.
References


2. Already in 2001, a few dozen plants using the supercooling principle had been developed in Japan; their capacity ranged from 700 kW with a storage capacity of 90 m³ to 3720 kW with a storage capacity of 1120 m³. Handbook on Ice Slurries – Fundamentals and Engineering. 291-301. IIR. 2005. www.iifiir.org


4. Some recently implemented plants and projects:
   - In Austria: brewery with two 350 kW Mueller vertical shell-and-tube with orbital rods and a storage capacity of 100 m³; Gibert V., Ice Slurry Experience, from the proceedings of the 7th Conference on Phase-Change Materials and Slurries, Dinan, France, September 13-15, 2006.
   - In France:
     a. 650 kW hypermarket with four 120 kW disk brushed-surface LGL/ALB generators with a storage capacity of 50 m³.
     b. 192 kW supermarket system with twelve 16 kW Flo-Ice double-tube generators and a storage capacity of 50 m³.
     c. 360 kW catering kitchen at the Agen hospital group (7500 meals/day) comprising four LGL/ALB 90-kW brushed generators, with a storage capacity of 50m³, being installed at the time of writing.
     d. 200 kW catering kitchen at the Eaubonne/Montmorency Hospital (4000 meals/day) with two 100-kW brushed disk LGL/ALB generators and a storage capacity of 25m³, being installed at the time of writing.

5. New systems presented at the Dinan conference in September 2006:
   - Flake-ice generator used by Frigofrance (France) to produce slurries. Vidal S., Slurry Production from a Flake-Ice Generator, in the proceedings of the 7th Conference on Phase-Change Materials and Slurries, Dinan, France, September 13-15, 2006.

New systems and systems being developed:
   - New “la sorbetière” generator using expansion under vacuum, developed by Technergie (France), soon to be tested by Cemagref at time of writing.
   - Modular 7-420 kW generators being implemented by Icegen Canada, featuring round plates of three different diameters.