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Introduction of FLO-ICE and Binary Ice technology as energy efficient and environmentally benign working fluids in the field of refrigeration and air conditioning

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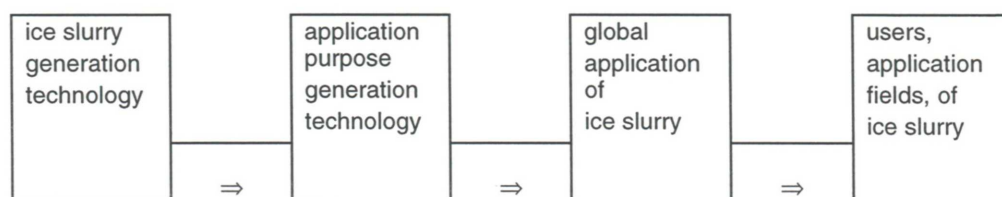
Executive summary

The 'ice slurry project is a joint industry - CEC RTD project to progress the adoption of ice slurry technology, and in particular of FLO-ICE™ and Binary Ice™ technology, as an energy efficient and environmentally benign technology for refrigeration and related purposes. The project has been carried out by a team drawn from TNO and Inham Refrigeration under the Specific Programme for Research and Technology Development (THERMIE) of the Commission of the EC, DG XVII. Other partners who provided contributions to the project are INTEGRAL Energietechnik GmbH, Solmecs FLO-ICE Systems Ltd. and Fri-Jado b.v.

Ice slurries are promising alternative possibilities to solve the problems caused by the phase-out of CFC's and HCFC's in refrigeration. This technology consists of a micro-ice slurry in almost pure water or in a mixture to change the freezing point. The main advantages of this technology are: energy efficient, environmentally benign, large latent heat content, high heat transfer coefficient, uniform temperature and low temperature difference in heat exchangers, energy storage and peak shaving possibilities, smaller pipe dimensions and reduced pumping work. One of the concepts of ice slurry, FLO-ICE™ and Binary Ice™ in development with Integral Technologie GmbH in collaboration with Solmecs Ltd and Inham-Refrigeration BV, is ready for market introduction in Europe. Binary Ice™ is the collective noun of Integral Technologie GmbH for FLO-ICE and vacuum ice, another ice slurry concept. The aim of the action is to support the breakthrough of this innovative technology by dissemination of experiences and stimulation of new applications in specific sectors of the Refrigeration and Air Conditioning industries within the EU.

First of all an assessment has been made of the state of the art concerning ice slurry technologies by carrying out a number of reviews. The reviews comprised a literature study and interviews with experts of various companies in this field. The reviews have been done in a structured way. To that end a scheme has been constructed.

The main steps of the scheme are as follows:



The first step, the ice generation technology, is meant to indicate the several ways, the principles and technologies, to produce an ice slurry as main or as side product. Also the characteristics of the systems, the specific secondary refrigerants to be

used and the status of the technology (lab, pilot plant, commercially available etc.) are indicated. The following principles are distinguished:

- vacuum crystallisation
Ice is produced by the means of vacuum crystallisation. Under triple-point conditions of water, ice crystals are generated which form a suspension of ice in water. No heat exchanger is necessary;
- scraped surface heat exchanger
A refrigerated surface (double walled drum or flat plate heat exchanger) is used to build a thin layer of ice. Before sticking to the surface, the building ice layer is removed from the wall by a scraper;
- binary solution
A refrigerated surface is used to supercool a binary solution without crystal nucleation on the surface. This can be achieved by:
 - an internal turbulator to agitate the binary solution inside a cooled tube,
 - by a falling film evaporator, the liquid acts as falling film,
 - by a fluidized bed chiller, binary solution with a suspension of small hard particles,
 - by applying a static electric potential to prevent the building of ice on the refrigerated surface,
 - by applying a strong binary solution;
- direct contact with refrigerant
Water and liquid refrigerant are combined in the freezer/evaporator where the refrigerant is vaporised by direct contact heat transfer with the water and a portion of the water is frozen to form a slurry;
- supercooling
Water or water mixtures are supercooled without crystal nucleation on the heat transfer surface or in the bulk fluid. Crystallisation is initiated after the supercooled water exits the evaporator.
- conventional ice making
In a batch process 'dry' solid ice (layers) is produced in a conventional way. This ice has to be processed further to achieve an ice slurry.

The second step states the application purpose of the generation principles/technologies. In most cases the main objective is to produce an ice slurry. However, an ice slurry can also be produced as a side product and is just a means to achieve another objective like serving as a heat source for a heat pump or separation (e.g. desalination of seawater) or concentration of solutions (e.g. juices, waste).

The following step aims at the global application of the ice slurry. What is or are the main objective(s) to choose for the use of an ice slurry, such as heat transfer, storage and/or transport.

The last step refers to the end users, the specific application fields, of a particular ice slurry.

The reviews reveal that a lot of installations working with different generating principles have been installed over the past years in a limited number of applica-

tion fields. Most of these installations are based on the principles 'vacuum crystallisation' and 'scraped surface heat exchanger', and to a lesser extent on the principle 'binary solution'.

Based on the reviews the most important factors for the introduction of ice slurry on a larger scale than so far has been realised, have been put in line. These factors deal with both technical and marketing aspects. The benefits of the use of ice slurries, as energy savings, environmental improvements by the replacement or minimisation of CFCs, HCFCs and HFCs, the problems and hurdles encountered for the introduction and some general hurdles for the introduction of a new technology like the general acceptance of a new, not yet proven or familiar, technology, etc. are described. The major stimuli for a market breakthrough are indicated as well.

In conclusion, the introduction of ice slurry technology makes a slow start. In a number of market segments specific applications of ice slurries are on their way and the possibilities for new applications are under continuous exploration. Sometimes technical problems hinder the use of ice slurry technology for certain users. But first of all, it is necessary to convince people of the benefits of ice slurry technology with respect to conventional refrigeration. To that end a structured marketing program is needed.

Just a few of the ice slurry generation principles have been developed into commercially available products. These technologies are mainly restricted to the scraped surface heat exchanger and to vacuum crystallisation. One of the main suppliers of scraped heat exchangers, and partly of vacuum installations, is Integral/Solmecs with their FLO-ICE network of licensees and sub-licensees.

The main conclusions are:

- Ice slurry technology, in particular FLO-ICE and Binary Ice, is technically feasible. However for a wide spread introduction of this technology some technical and non-technical aspects have to be assessed.
- Using ice slurry technologies, energy savings between 10 and 20% are expected in most applications for optimised systems.
- The applications of ice slurry technologies make it possible to use natural refrigerants like ammonia and hydrocarbons as replacements for ozone depleting and/or global warming substances like CFCs, HCFCs and HFCs.
- Ice slurry technologies are economically feasible in future depending on the opportunities for a real market breakthrough. Technological developments and market penetration play an important role in this.

A number of technical and non-technical aspects have been selected which need further attention. Further elaboration of these aspects is considered as a necessary condition for a wide spread introduction of ice slurry technology, and especially FLO-ICE and vacuum ice.

The recommendations indicate how the selected aspects can be dealt with, which approaches are proposed.

Technical aspects

- Storage vessel. A design guideline for the storage vessel, integrated in the system, has to be drafted. The guideline has to be based on a newly to develop and to validate model.
- Secondary refrigerant. The technical and health characteristics of the solutions (water mixtures) have to be investigated. Which freezing point depressives (and dopes as well) in which concentration are applicable and allowed at which temperatures for direct and indirect use in ice slurries has to be assessed.
- Further development of flat plate heat exchanger. To extend the capacity of the scraped drum a scraped flat plate heat exchanger is in development. The pilot scale apparatus has to be transformed into a commercial, cost-effective and energy saving product.
- Further development of vacuum ice plant with conventional refrigeration equipment. This type of vacuum ice plant is meant as a capacity extension to the scraped drum for temperatures of approximately 0 °C. For a fast development of the test apparatus into a commercial product strong support is needed.
- Defrosting, freeze applications. The problem of defrosting stands out particularly in freezer cabinets for commercial refrigeration. An evaluation of the possibilities and experiences with already installed freeze applications has to lead to an optimized defrosting qua energy consumption, performance, reliability, etc.

Non technical aspects

- Real world examples. To demonstrate the benefits of a new technology it is necessary to have full scale plants operating, preferably in several application fields. Real world applications have to be created and carefully supported to get an independent observation of their performance and their advantages.
- Price/performance relation. An investigation of the capital and running costs, and eventual the whole life cycle costs, is necessary to have a solid base for comparison with conventional refrigeration systems. The performance can be characterised by a number of items. A decision analysis model has to be drafted to value each of the characteristics into a total judgement, so for each situation a more objective decision can be made pro or against ice slurry.
- Education and training for designers, manufacturers, installers and end-users. A comprehensive route of training and education to introduce the ice slurry technology into the market has to be started.
- Public relations. A PR programme has to be set up indicating which groups have to be addressed, by who and in which way.
- Technology network including equipment suppliers, installers, end-users. To promote the possibilities of ice slurry technology, to exchange experiences and to explore new applications a structured technology network is very useful.

Table of contents

Executive summary	2
1. Introduction.....	8
2. Ice slurry technologies: state of the art.....	11
2.1 Framework.....	11
2.2 Approach reviews	14
3. Reviews.....	15
3.1 Ice slurry generation.....	15
3.1.1 Ice generation by vacuum crystallisation.....	15
3.1.2 Ice generation by scraped surface heat exchanger	17
3.1.3 Ice generation within binary solution.....	18
3.1.4 Ice generation by direct contact with refrigerant	21
3.1.5 Ice generation by supercooling	22
3.1.6 Ice generation by producing ice layers.....	23
3.2 Application purposes	24
3.2.1 Ice slurry.....	24
3.2.2 Heat source.....	25
3.2.3 Separation/concentration.....	26
3.3 Global application/users	26
3.3.1 Storage	26
3.3.2 Transport	27
3.3.3 Heat transfer.....	28
3.3.4 User applications given by interviewed companies.....	30
4. Experience, realisations	32
4.1 Vacuum crystallisation	32
4.2 Scraped surface heat exchanger	32
4.3 Binary solution	35
4.4 Ice layers/flakes	35
5. Investigation of technical and marketing requirements	36
5.1 Integral aspects ice slurries.....	36
5.2 Energy savings and environmental benefits	37
5.3 Present situation refrigeration branch	40
5.4 Market aspects	41
5.5 Present situation FLO-ICE network	44
5.6 Requirements users/market segments.....	45
5.7 Selected aspects	48
6. Conclusions.....	49

7.	Recommendations and exploitation of results	50
8.	References.....	53
9.	Authentication.....	60
Appendix A	Questionnaire	
Appendix B	Results of the questionnaire	
Appendix C	Licensees of FLO-ICE	

1. Introduction

The 'ice slurry' project is a joint industry - CEC RTD project to progress the adoption of ice slurry technology, and in particular of FLO-ICE™ and Binary Ice™ technology, as an energy efficient and environmentally benign technology for refrigeration and related purposes. This project is being carried out by a team drawn from TNO and Inham Refrigeration under the Specific Programme for Research and Technology Development, including demonstration in the field of non-nuclear energy (THERMIE) of the Commission of the European Communities, DG XVII (Contract No. SME-0112095-NL). Other partners who provided contributions to the project are INTEGRAL Energietechnik GmbH, Solmecs FLO-ICE Systems Ltd. and Fri-Jado b.v.

The phase-out of CFC's and HCFC's in refrigeration causes very serious problems due to a lack of acceptable alternative fluids. The most promising future alternatives are ammonia and hydrocarbons (butane, propane etc.). However, these fluids can only be used in very compact refrigeration systems with a minimum refrigerant content in combination with a secondary refrigerant system. Traditionally used brines as secondary refrigerant do have many technical and environmental drawbacks. One of the handicaps is the relatively small specific transport capacity for cold, because only sensible heat plays a part. Water and water mixtures as refrigerants also have high viscosity at low temperatures which requires more pumping work.

Ice slurries are very promising alternative possibilities, being energy efficient and environmentally benign. This technology consists of a micro-ice slurry in pure water or in a mixture to change the freezing point. The main advantages of this technology are: energy efficient, environmentally benign, large latent heat content, high heat transfer coefficient, uniform temperature and low temperature difference in heat exchangers, energy storage and peak shaving possibilities, smaller pipe dimensions and reduced pumping work.

One of the concepts of ice slurry, FLO-ICE™ and Binary Ice™ in development with Integral Technologie GmbH in collaboration with Solmecs Ltd and Inham-Refrigeration BV, is ready for market introduction in Europe. Binary Ice™ is the collective noun of Integral Technologie GmbH for FLO-ICE and vacuum ice, another ice slurry concept. The aim of the action is to support a breakthrough of this innovative technology by dissemination of experiences and stimulation of new applications in specific sectors of the Refrigeration & Air Conditioning industries within the EU.

The project has 2 phases:

Phase 1: Technology exploration

The possible application fields of the technology (i.e. supermarket refrigeration, fish chilling, air conditioning etc.) will be examined. Pro's and con's of this technology will be made explicit, based on the specific experience of the proposers and

their individual network relations. Needs for additional research development, engineering, maintenance, marketing, demonstration etc. will be identified.

Detailed work programme:

- evaluation of the Dutch report 'Indirecte koeling d.m.v. FLO-ICE' (Indirect refrigeration by FLO-ICE) [0] with emphasis on the market segmentation in the Netherlands;
- inventory of the existing knowledge and applications of slurry ice;
- formulation of a questionnaire for Fri-Jado, Integral, Solmecs and Inham concerning experience with slurry ice, pro's and cons, in specific fields and concerning market possibilities;
- filling in the questionnaire in writing by or via the above mentioned companies to get the actual state of the art in Europe, if necessary a meeting will be arranged;
- concept interim report, identification of the needs for additional research for already existing applications based on the actual experience, and identification of the needs for additional research for promising application fields;
- interim report, including the comments of Fri-Jado, Inham, Integral and Solmecs on the concept report.

Phase 2: Investigation of the technical requirements

The technical requirements for the adaptation of this technology in promising application fields or sectors, identified in phase 1, will be investigated.

Detailed work programme:

- decision point,
which of the topics, identified in phase 1, will be subjected to a further, more detailed, investigation, and which of the topics will be globally examined? dependent on the priorities, means, available time and money etc.
- formulation of the work programme for the detailed and global investigation(s);
- execution of the detailed and global investigation(s) according to the work programme;
- concept interim report;
- interim report, if besides Inham other companies are involved in the further investigations, their comments will be worked into the interim report;

As the completion of the questionnaire took more time than foreseen, it was decided to adapt the work programme. Phase 2 is based on the information gathered in the first phase completed by the results of bilateral consultation with the partners. Instead of two interim reports with a comment round, the draft final report was sent for comments and screening.

This report gives an overview of the state of the art concerning ice slurry technologies, promising applications of these technologies, required technical development and market policies for the adaptation of these technologies in promising application fields or sectors and indicates with topics need further attention and in which way.

The original project proposal under the THERMIE Programme also comprises phase 3: Training activities, and phase 4: Demonstration activities. Phases 3 and 4 are not part of the work under the current contract. In chapter 7 recommendations for the execution of these phases are given.

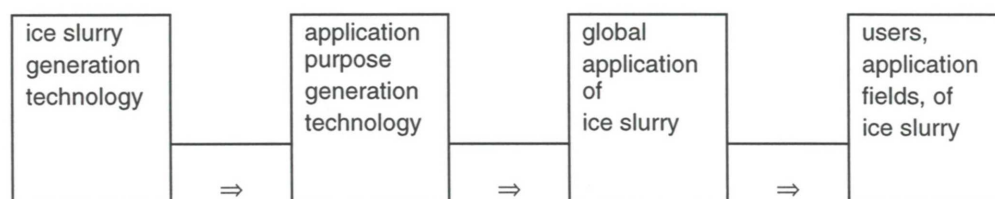
2. Ice slurry technologies: state of the art

A number of reviews were carried out to try to assess the current status of ice slurry technologies and applications. These included a literature review and interviews with experts of various companies in this field. In this way existing knowledge and experience concerning ice slurries have been collected.

These reviews together enabled a good overview to be gained of the current status of ice slurry technology and application, and highlighted a number of areas that will be followed up on the next phase of the project.

2.1 Framework

For a structured approach the reviews have to be placed within a framework. To that end a scheme has been constructed (see following page and appendix A). The original scheme (appendix A) is based on some provisional study results. The scheme on the next page shows the eventual classification. The main steps to be distinguished in the scheme (the left column) are as follows:



The first step, the ice generation technology, is meant to indicate the several ways, the principles and technologies, to produce an ice slurry as main or as side product. The second step states the application purpose of the generation principles/technologies. In most cases the main objective is to produce an ice slurry. However, an ice slurry can also be produced as a side product and is just a means to achieve another objective.

The following step aims at the global application of the ice slurry. What is or are the main objective(s) to choose for the use of an ice slurry?

The last step refers to the end users, the specific application fields, of an particular ice slurry.

These four main steps have been further elaborated in the scheme. For each main step some examples are given.

The right column in the scheme is reserved for the essential characteristics belonging to each main step. The further specification of these characteristics depends on the specific fulfilment of the main step considered.

The scheme is meant as an aid during the reviews and is to be used as a starting point. The literature study and the interviews have to supply the necessary information to complete the scheme as good as possible. By filling in the specific requirements of a user, the characteristics of the ice slurry and with that, the way of generation and the used medium/mixture, can be determined. In that way insight can be gained into the possibilities and impossibilities of ice slurry. The objective is to get answers to questions like: 'What are the pro's and con's in which application field? What are the most promising fields and why? What need to be done to realise a real market implementation? Which additional research, development, engineering, maintenance, marketing, demonstration, etc. is needed?'.

Main steps	Possibilities						Characteristics
ice generation	vacuum, crystallisation, direct freeze (triple point), single/two stage systems	scraped surface heat exchanger	ice generation in binary solution, not at tube evaporator · strong binary solution, internal wiper, falling film, vertical shell and tube, · static electric potential · fluidized bed	direct contact water and circulating, refrigerated fluid, not mixable with water	super cooling recrystallisation initiated after supercooled water exits evaporator (modified shell and tube)	defrost cycle ice generator conventional ice making + additional processing for slurry	capacity, temperature range, media, energy consumption, commercially available, etc.
application purpose	heat source (heat pumps) ice slurry separation/ concentration (desalination, oil/water separation, juice concentration)						pumpable, temperature, composition, ice concentration, viscosity, enthalpy, etc.
global application	storage transport heat transfer refrigeration/freezing ice (harvesting) (flake, crushed) direct contact indirect contact, secondary refrigerant direct contact						way of application
user	variable loads (peak shaving), discontinuous operation, time dependent energy prices, etc. district cooling, refrigeration installation at distance (R717, R290, ..), flexible use, etc. fish, agriculture products, concrete, displays, etc. air-conditioning, supermarket cooling/freezing, dairy industry, food industry, process cooling etc. fish, concrete, meat, display etc.						specific application requirements: composition, temperature, toxicity, capacity, new/existing installations, legal requirements, etc.

Scheme ice slurry

2.2 Approach reviews

The literature review is based on a general search of open literature regarding ice slurries and on articles and documentation of FLO-ICE suppliers. The appropriate articles, reports, patents and documentation have been studied. A reasonable number of references were found and reviewed. These covered the principles of ice slurries, example applications and some discussion of the main hurdles and drivers affecting the way ice slurry issues are addressed.

The review found that a number of references repeated the same points. Although the references often listed some of the hurdles to adopting ice slurries, few related any practical experience of how best to overcome these. As a result few of the papers could offer any practical, tried and tested, advice on how to promote the use of ice slurries.

The review of the market segments suitable for ice slurries is based on the 'graduation' report [0] about the application possibilities of FLO-ICE, in particular in the Dutch market.

The interviews with a sample of relevant companies have been carried out by means of a questionnaire. The questionnaire consists of a general part to get some background information of the working field of the company and the person to be interviewed, and of a specific part to get information of all kind of items with respect to the topic ice slurry. The questionnaire is included in appendix A. The questionnaire was sent to eight companies working in the field of ice slurries, with emphasis on the commercially available concept of FLO-ICE.

3. Reviews

The results of the reviews are grouped and reported according to the classification of the 'scheme ice slurry' (see chapter 2.1).

3.1 Ice slurry generation

There are several ways to generate an ice slurry intended as main or as side product. The technology status of the various principles ranges from an idea, a laboratory scale experimental installation, a patent, a pilot plant, a demonstration unit to a full commercial product. The characteristics of the ice slurry are (partly) dependent on the production principles/technologies.

3.1.1 Ice generation by vacuum crystallisation

Methodology

This technology uses water as a refrigerant. Ice is produced by the means of vacuum crystallisation. At the same time evaporation and cooling occur under sub-atmospheric conditions. Under triple-point conditions of water at approximately 6 mbar (abs) and 0 °C ice-crystals are generated which form a suspension of ice in water. The heat for evaporation is in a direct contact process extracted from the sensible heat from the solution and the crystallisation. No heat exchanger is necessary. The handling of the water vapour can be done in two ways.

- Compression and condensation:
The generated water vapour is removed from the expansion vessel (evaporator) and compressed with a vapour compressor (mechanical or thermal energy (ejector)) in single- and multistage arrangement. The subsequent condensation can take place by various methods, indirect via a heat exchanger or via direct contact (without heat exchanger).
- Desublimation:
The generated water vapour is sublimated on an evaporator inside the expansion vessel (vacuum-freeze evaporator).

For a good performance a marginal amount of a temperature decreasing substance (like a salt) has to be added.

[1, 3, 71, 5, 13, 15, 31, 35, 53, 57, 74, A]

Characteristics

Plants with water as refrigerant are extremely insensitive towards the water quality since no heat exchangers exist which may suffer from fouling or precipitation. The ice slurry is fully degassed and oxygen corrosion is almost completely excluded. Inert gases are removed by a vacuum pump in the sublimation process.

The energetic advantage of vacuum ice plants stems from the non-existing losses in the heat exchanger(s). A temperature difference of only approximately 0,5 K can be achieved which saves at that side of the process some 10K.

Installations based on water vapour compression and condensation:

The main hurdles for these types of installations are:

- the specific volume of water vapour at low temperatures is enormous which necessitates compressors with a large swept volume;
- the ratio between condensing and evaporating pressure is relatively high and lies - depending on the conditions - typically between 5 and 7.

Therefore compressors are needed which can accommodate some 100.000/1.000.000 m³/h of swept volume at high pressure ratio. Also the compression end temperature is high.

Capacities can range from 150 kW to 8 MW. These systems are commercially available (e.g, Integral: installations up to approximately 9 MW, production capacity 350 ton ice/day and 600 ton ice/day per unit, cost per by kW installed: approximately 420 ECU per kW refrigeration; Sabroe (Denmark): vacuum ice/heat pump plant, 170 ton ice per 24 hrs.; IDE (Israel): 700 ton ice per 24 hrs (@ 3MWR per typical unit); Calfran International (USA)). Research is going on, by for instance, DTI (Denmark) and NRCC (Canada, 10 ton pilot plant).

Installations based on water vapour (de)sublimation:

Defrosting of the evaporator can be done in several ways for instance:

- by hot gas, batch process;
- by hot gas, intermittent two evaporators, continuous process;
- by temporary raise of water vapour pressure in the vessel, defrosting of the ice as result of direct contact heat transfer between condensing water vapour and melting ice; the pressure raise is achieved by injection of warm water (8 → 30 à 35 °C); flash evaporation of this water causes a very rapid raise of the water vapour pressure, resulting in a very short defrost period and an almost continuous process.

At Inham Refrigeration a pilot plant built with ordinary refrigeration components is being developed and is now in his test phase. The primary medium is ammonia. This technology is interesting for capacities above 1 MW .

Some variations, improvements or other kind of realisations of vacuum ice installations are mentioned in the patent literature [61, 64, 66].

The slurry is a suspension of tiny, partly microscopic ice-crystals. The temperature is about 0 °C (-0,5 °C). After crystallisation a slurry of about 20% ice and 80% water is generated, dependent on the inlet temperature. It is hardly possible and certainly not feasible to generate ice slurry at temperatures much lower than ± 0 °C, because of the large increase of necessary swept volumes.

3.1.2 Ice generation by scraped surface heat exchanger

Methodology

This type of generator uses a refrigerated surface to build a thin layer of ice. The surface is refrigerated using conventional technology appropriate for the low temperature application.

The ice is formed at the inside of a double walled drum. The refrigerant evaporates in the space between inner and outer wall. The drum is closed at the upper and lower side. The liquid is supplied at the upper side of the drum. Before sticking to the surface, the building ice layer is removed from the inner wall by a scraper. Together with the liquid the ice crystals are transported out of the drum to the user or to a storage tank.

Instead of a drum type heat exchanger a flat plate heat exchanger can be used in the same way.

For a good performance, for instance the prevention of the forming of 'hard' ice and for good transport properties, a temperature decreasing substance, like glycol, alcohol, salt solution etc. has to be added. Due to the added freezing point lowering substance, the concentration of the substance in the liquid increases as ice is generated. The increased concentration depresses the freezing point further and lowers the overall thermodynamic efficiency of the process as ice is produced. However, lower temperature may be an advantage for some applications. The substance has to be non toxic, non corrosive and completely soluble in water.

[0, 1, 3, 7, 9, 13, 14, 17, 16, 23, 27, 30, A, B, C, E]

Characteristics

The system is commercially available in ranges from 1kW to 180 kW per unit (FLO-ICE, company Integral and license holders). Typical capacities for the scraped vertical drum type range between 1 and 75 kW and for the flat plate type from 50 to 500 kW, not yet commercially available. Another supplier of scraped tube exchangers (Deepchill, company Sunwell) did use horizontal tubes for the ice generation, but uses now vertical drums as well.

The only difference with a conventional refrigeration system is the replacement of the evaporator by the ice generator. Due to the possible compactness of the generation system, same location for the refrigeration system and scraped drum, only a relatively small charge of an (environmental benign) refrigerant in the conventional system is needed.

In comparison to ice builders or ice banks a high efficiency is possible due to the smallness of the ice crystals, just a thin layer of ice is built up without reducing the heat transfer and with that without lowering the evaporation temperature. Only a decrease of the temperature due to the ice built up in the solution takes place.

This system can be operated with every appropriate brine or aqueous solution. Substances to be used are ethanol (+ an inhibitor), salts like NaCl or seawater and sugars. The liquid/ice mixture can be processed or stored in various ice fractions. The ice fraction increases with the operating time of the installation. The slurry is pumpable to ice fractions of about 35% à 50%.

The temperature range is depending on the medium applied and the ice fraction. A wide temperature range is possible from -1°C (seawater, $-1,8^{\circ}\text{C}$ at 3,5% salt) to -40°C (ethanol) and even lower.

Due to the special way of production (FLO-ICE) the ice crystals don't melt together, but for buffering during a longer time in a storage tank a stirring device is necessary to keep the ice slurry pumpable.

Some data of FLO-ICE installations, as delivered by various license holders: Inham (licensor), sells standard units with the following characteristics: nominal capacities of 2,5, 5,0 and 7,5 ton ice per 24 hours, direct contact installations without storage tank and sea-water as medium, indirect contact installations with storage tank and ethanol solution as medium, costs about 1650 ECU per kW refrigeration installed, primary refrigerant R507 or R22, temperature range ethanol solution $-4 \rightarrow -6^{\circ}\text{C}$, sea-water $-1,9 \rightarrow -2,3^{\circ}\text{C}$.

Integral: installations of approximately 2,5 MW, production capacity 0,5 - 50 ton ice per 24 hours per unit, cost per kW installed approximately between 550 and 1100 ECU per kW refrigeration, primary refrigerants preferably natural substances such as propane, ammonia etc., ice slurry consisting from ice water mixture with small amount of additives such as ethanol, NaCl etc., temperature range slurry $-1 \rightarrow -40^{\circ}\text{C}$.

Star: 'concentration loop' development of larger drum with new type scraper, larger system more suitable for sea-water applications and a higher capacity, approximate cost 1300 ECU per kW refrigeration for a 3,5 to 35 kW refrigeration system, major benefit of the new system is the use of lower salt concentrations, 1% NaCl solution, primary refrigerants ammonia and R22, minimum temperature of the ice slurry with ethanol $\approx -30^{\circ}\text{C}$.

The internal wiper/scraper system (DEEPCHILL, Sunwell company) is constructed from one or more relatively large diameter horizontal tubes which are chilled at the outside. Mechanically driven wipers rotate inside the tube(s) to continuously disturb the solution boundary layer at the tube wall. The agitation keeps a uniform temperature throughout the bulk of the solution as well. The chilled solution is moved away from the wall prior to crystal growth. Ice slurry makers are available that can operate with an ice slurry fraction of up to 25% per pass. Ice crystals are in the range of 0,03 to 0,05 mm, during storage the crystals can grow to 10-20 times the original size.

3.1.3 Ice generation within binary solution

Methodology

This type of ice slurry generator uses a refrigerated surface to supercool a binary solution without crystal nucleation on the surface. The surface is refrigerated using conventional refrigeration technology appropriate for the low temperature application. The ice is formed in the bulk fluid away from the refrigerated surface. This technology can only operate with a binary solution which depresses the freezing

point of water. Successfully used freezing depressants are ethylene glycol, propylene glycol and salt solutions.

Several methodologies are known to achieve crystal growth in the bulk fluid:

- a. internal turbulator to agitate the binary solution inside a cooled tube. Agitation prevents ice forming on the cold surface by control of the thermal boundary layer;
- b. falling film evaporator, where the liquid acts as a falling film along the inner surfaces of cooled tubes. The falling film flow pattern, a special tube finish, and a controlled maximum heat flux, combine to eliminate ice growth on the tube surfaces (special case of e.);
- c. fluidized bed chiller, (weak) binary solution with suspension of small hard particles (like glass, steel). particles prevent the building of ice on the refrigerated surface;
- d. static electric potential to prevent the building of ice on the refrigerated surface;
- e. application of a strong binary solution, with the disadvantage of a raise in the energy consumption by the lowering of the freezing point.

One of the interviewed companies mentioned the production of ice on a vibrating plate (wall).

[9, 13, 19, 21, 27, 31, 40, 63, 73, 74, A]

Characteristics

The ice slurry produced by these designs has roughly spherical ice grains ranging from 0.1 mm to 0.25 mm in a binary carrier fluid, usually water/glycol. The fine crystal size associated with these systems is the result of concentration gradients generated during the crystallisation process. When a binary fluid is chilled below its freezing point, spontaneous nucleation initiates the growth of an ice crystal. The crystal being formed is composed of pure water extracted from the binary solution during the phase change process. As a result, the liquid in the immediate vicinity experiences an increase in concentration. The freezing point of this fluid drops proportionally with the increasing concentration. Eventually, the freezing point is depressed to the point where continued crystal growth is not thermodynamically possible. This process comes about quite rapid resulting in the termination of crystal growth while the crystals are relatively small.

The flow characteristics at moderate ice concentrations (< 30%) for this slurry are similar to those of the binary solution alone (homogeneous and Newtonian).

The commercially available, internal turbulator system, system a., (MaximICE, Paul Mueller Company) features a unique shell and tube evaporator (Orbital Rod Evaporator, ORE). A water/7% propylene glycol solution flows to the top of the vertical evaporator tubes, then flows downward through the tubes where it is cooled to about - 2 °C by refrigerant in the shell. The ice forms in the tubes, where constantly rotating rods serve to increase heat transfer rates and keep the ice from coagulating or sticking to the walls. The pumpable slurry is stored in a tank. Inorganic brines have also been used successfully in the system. To satisfy a cooling demand, a pump draws cooled liquid from the bottom of the tank and delivers it to

the load. Warmed solution is sprayed into the top of the tank. A full tank contains about 50% ice and the fine ice crystals enable a low solution temperature to be maintained until the ice is nearly used up. Recommended is a plate/frame heat exchanger between the slurry and the cooling load. A line of MaximICE models offers ice-making capacities ranging from 3 to 520 tons (nominal 6-, 25-, 50-, 100- and 400- ton units). The 25-ton ORE, to give an idea of size, stands 58x46x88 inches, weighs 3000 pounds in operation, and features a ¾-hp motor. Prices for the ORE alone are \$6000 for a 3-ton unit, \$25000 for a 25-ton model, \$38000 for 50-ton unit, and \$56000 for a 100-ton-unit.

The falling film type, system b., is essentially a vertical shell and tube evaporator with the tubes extending above the upper tube sheet. The binary (ethylene glycol) solution is distributed uniformly over the upper tube sheet where it overflows the rim of the extended tubes creating a falling film along the inner surface of the tubes.

The concept of the fluidized bed chiller, system c., is based on existing fluidized bed heat exchangers meant to be used for polluted fluids in the industry. The exchanger consists of a great number of parallel tubes, wherein the solid particles by the fluid flowing through the tubes, stay in a stationary condition. This concept is in development.

The direct production of ice slurry in an evaporator fitted with static electric potential to keep ice particles away from surfaces, system d., (2% additives) is described in patent literature and a prototype is known.

A new concept without moving scrapers, system e., is proposed and built as a laboratory demonstration unit (research institute DTI). The binary solution flows through a long horizontal tube which is cooled at the outside. The evaporator, a simple spiralled tube, produces an ice slurry of the required concentration. The technology is based on the combination of special treatment of the heat exchanger surfaces and the addition of special additives to the slurry. The ice generator uses ammonia as refrigerant. Preliminary tests with the prototype look very promising. The technology is patented world-wide and is currently under development at DTI in close co-operation with a Danish refrigeration equipment manufacturer. Another approach, called Slippery Ice, was developed by EPRI (USA). It was found that the addition of calcium magnesium acetate to the water produces ice that slides right off the surface on which it forms. Compared to the mechanical complexity in case of the scraped surface technology stands the expensive water treatment in the case of slippery ice. EPRI has received patents for its water chemistry, but so far has little field experience. A unit was installed at a mushroom farm but testing has been delayed due to problems on the process side of the operation.

The freeze exchanger can be a shell and tube freeze exchanger with vertical tubes in which the aqueous liquid is cooled and ice produced by downward flow of the aqueous liquid in the tubes (or more in particular a falling film type, see system b.). Ice produced is in the form of small crystals which readily flow with the aqueous liquid (Chicago Bridge & Iron Company).

Commonly used freezing depressants for these systems are:

- ethylene glycol,
environmentally hazardous; in many areas systems have to be constructed with double walled pipe (additional cost penalty) to guarantee leak proof operation;
- propylene glycol,
environmentally non-hazardous, more expensive than ethylene glycol;
- salt solutions,
corrosion problems within heat transfer equipment and transport lines (economic consequences).

3.1.4 Ice generation by direct contact with refrigerant

Methodology

The direct freeze system is based on a direct contact evaporator/freezer. Fresh water and liquid refrigerant are combined in the freezer/evaporator where the refrigerant is vaporised by direct contact heat transfer with the water and a portion of the water is frozen to form a slurry. The refrigerant vapour, with or without separation from the ice slurry, is recycled using a vapour compression cycle.

Another direct contact system makes use of a heat transfer fluid as an intermediate. The heat transfer fluid, after being cooled with a conventional refrigeration plant, is brought in direct contact with water.

[9, 12, 19, 24, 25, 29, 31, 72, 74]

Characteristics

The direct contact design allows the evaporator/freezer to operate with a minimal temperature difference between water and refrigerant. Also, high refrigerant evaporation temperatures, up to -1 °C, provide optimum thermodynamic efficiency. The direct contact approach yields very high heat transfer rates and eliminates the need for a heat exchanger. The approach requires a containment scheme for any refrigerant that gets entrained in the ice.

When the refrigerant is not separated from the ice slurry, this technology cannot be implemented with 'off the shelf' refrigeration equipment due to the super saturated mixture of refrigerant vapour and water which exits the direct contact evaporator. All the other components have to be customised. Continuous operation has been demonstrated.

The system produces an ice slurry directly with ice fractions as high as 10% per pass.

The ice slurry consists of large crystals which are roughly spherical in shape with a jagged surface texture. The crystal size ranges from 3 to 6 mm diameter. The rela-

tively large, uniform crystals are the outcome of eliminating freezing depressants and providing adequate residence time. The larger ice crystals exhibit a non-Newtonian behaviour which results in lower pressure drop than chilled water at the same velocity.

The refrigerant must be relatively insoluble and essentially inert in water to prevent chemical reactions and meet the environmental requirements. Possible identified existing refrigerants to be used include C-318 and butane. Chicago Bridge & Iron Co. offered such a system several years ago, but concerns about CFCs forced the company to abandon the concept.

Recently Kajima Corp. of Tokyo introduced a direct-contact ice slurry product that is called the Flash Freeze System. The system uses non-toxic, non-flammable perfluoropentane as refrigerant. In this approach a mixture of water and refrigerant is sprayed into a depressurized tank, causing the refrigerant to vaporise and the water to cool/freeze. A compressor draws off the vapour and sends it through a condenser and then mixes it with water and feeds the mixture back into the tank. Ice is produced as the process is continuously repeated.

The direct/indirect system uses a conventional refrigeration plant to cool down a heat transfer fluid to a temperature below 0 °C. The heat transfer fluid and the water are brought into direct contact with each other (developed by EA Technology). In a storage tank three layers exist. The upper layer is formed by ice slurry, the middle layer by cold water and the lower layer by the heat transfer fluid. The heat transfer fluid is not mixable with water and is heavier than water. In a venturi nozzle ice slurry is formed from the water coming from the middle layer by direct contact with the heat transfer fluid coming from the evaporator. The mixture of ice slurry and heat transfer fluid is led to the lower layer. The ice slurry floats to the top of the tank. The company is intended to test a full-scale, 50 kWh unit, to supplement a milk cooling system on a dairy farm.

3.1.5 Ice generation by supercooling

Methodology

The supercooled ice slurry generator uses a modified conventional shell and tube evaporator to supercool fresh water without crystal nucleation on the heat transfer surface or in the bulk fluid. Crystallisation is initiated after the supercooled water exits the evaporator.

[9, 19, 20, 26]

Characteristics

Conventional refrigeration technology appropriate for low temperature application is used in conjunction with a novel shell and tube evaporator, refrigerant on the shell side and water inside the tubes. After the supercooled liquid exits the evaporator, the crystallisation process can be initiated immediately, or delayed until de-

sired. The crystallisation process can be initiated by directing the supercooled water over a flow obstruction. Depending on the degree of supercooling, approximately 2 to 3% ice per pass can be generated.

The size and shape of the crystals can be controlled by varying the operating conditions of the evaporator and by carefully selecting the method used to initiate nucleation. This control opportunity is a significant advancement to achieve the optimum hydraulic behaviour for the distribution and storage of the ice crystals ('Superpac' (supercooling pompe à chaleur) developed by Laval University). A demonstration unit has proven the technical feasibility, other units are in commercial operation. Achieving high ice fractions in slurry form is essential, for each degree of subcooling the ice fraction increases by about 1,25%. Controlling crystallisation to prevent ice building in the evaporator is critical in system operation. Besides supercooling of water to about -2 °C, it is also possible to supercool water/ethanol mixtures in a shell and tube or coaxial evaporator. The initiation of ice crystals occurs for instance as the supercooled fluid contacts any part of the ice slurry reservoir or for instance jets an endless belt located above a cold water reservoir, the belt acts as a nucleator, as a water/ice separator and as ice mover. Any water, pure, saline, polluted, at any inlet temperature can be applied.

3.1.6 Ice generation by producing ice layers

Methodology

Ice can be generated in several ways. This conventional type of ice generator produces ice which has to be processed to achieve an ice slurry. Unlike the scraped surface ice slurry system, which is a continuous process producing a combination/solution of fluid and very tiny ice particles, the conventional ice generating systems are batch process oriented and produce 'dry' solid ice. The generator uses a refrigerated surface to build a layer of ice. The insulating property of ice reduces the efficiency of ice generation as the ice layer continues to build. To minimise this effect, the layer has to be removed continuously or from time to time.

- removal of ice by scraper(s),
Ice is formed from water which flows over the chilled surface of a drum. The ice layer is continuously scraped from the surface of the drum by a knife;
- removal of ice by cyclic defrosting,
Ice is formed from water which flows down over an refrigerated surface, which can be made in variety of shapes (most common tube or plate). The ice thickness is limited to a predetermined thickness of approximately 1 cm before the refrigeration cycle is reversed sending hot refrigerant over the refrigerant surface.

[19, 25, 27, 31]

Characteristics

The ice generators are commercially available from several suppliers.

The scraped drum system produces a combination of ice shavings and excess water

which could be handled as a slurry. Further processing may be required to achieve the desired type of ice slurry. Actual attempts to generate an ice slurry have not been reported. Scrapings can also be blend with a weak binary solution.

The cyclic defrost system produces sheets or annuli of ice in a batch process. Additional processing would be required to achieve a continuous supply of ice slurry with the desired properties. Actual attempts to convert the ice into a pumpable ice slurry with a continuously supply, have not been reported.

The composition consists of hard ice crystals in solution, bad for direct contact. This type is used in the fishing industry. The commercially installations of this type have a capacity of maximal 50 ton hard ice per 24 hours. The primary refrigerants used are CFCs or HCFCs. The temperature of the ice slurry is $\geq -2,5\text{ }^{\circ}\text{C}$ (first subcooled ice) [A].

3.2 Application purposes

Ice slurry generators can be applied solely to produce an ice slurry which can be used for cooling purposes or to achieve an other objective which benefits from the generation process. Of course optimal results could be attained by combining more than one purpose. As example installing a vacuum freeze evaporator as part of large heat pump installations provides the opportunity for combining heating, cooling and (sea-)water desalination in a cost advantageous way . Besides acting as a heat source for the heat pump, the freezing operation also yields ice which can be used for long- or short-term storage of cooling capacity. Because ice is formed in a pure crystalline form, potable water can be obtained after washing and melting of the ice crystals [35].

3.2.1 Ice slurry

A number characteristics of ice slurries are already mentioned in former paragraphs about the generation principles. This paragraph deals with some more aspects.

Ice slurries are in principle environmentally benign.

Ice slurry is a pumpable substance at least up to a certain ice fraction. It behaves up to ice concentrations of about 20 à 30 % and velocities less than 2 m/s more or less as a Newtonian fluid (2, 7, 16). Tests with a water/ethylene glycol (6%) ice slurry containing spherical crystals with diameters in the range from 0,1 to 0,25 mm and a smooth exterior texture, show no essential change in pressure drop comparing to chilled water/glycol mixtures. At least up to ice fractions of 16 to 30% depending on the flow velocity the similarity holds. This maximum ice fraction increases with higher fluid velocities. For the same fluid velocity the maximum ice fraction increases with for larger pipe diameters.

The flow characteristics of coarse fresh water ice slurries are complex and non-Newtonian. This type of ice slurry is for instance produced by the direct freeze

method. Ice crystals are spherically in shape with a rough exterior texture and with diameters of approximately 5 mm. Agglomeration in the form of ice clusters in the flow appear. A reduction in pressure drop of over 40% relative to water at the same mass flux occurs. The pressure drop of the ice slurry decreases gradually with increasing ice fraction down to its minimum level as the ice fraction approaches 8 to 10%. The pressure drop reduction remains essentially constant for increased ice fractions up to 16%.

The ice crystals consist of pure water surrounded by a more or less concentrated 'brine' (non freezing liquid).

The latent energy is responsible for its high energetic density. This latent heat is fully available at the generation temperature. The latent heat means a reduction in pipe diameters for ice slurry and lower pumping power in comparison to water or to other secondary refrigerants like brines etc. Ice slurries can be used to achieve higher capacities in existing indirect cooling installations.

The possibility to use ice slurry (high energetic density and good heat transfer) instead of a boiling refrigerant in direct expansion systems means a small refrigerant charge is sufficient. In consequence to this and to the possible spatial separation between refrigeration unit and user, 'hazardous' but environmentally benign working fluids, such as ammonia or hydrocarbons, can be applied.

Because of its latent energy part ice slurry is also suitable for thermal storage and the transport of cold energy.

[1, 8, 19, 20, 3, 17, 71]

3.2.2 Heat source

During the generation of an ice slurry the latent heat extracted from the fluid serves as heat source for a heat pump. The need of water is many times smaller than when using exclusively the sensible heat of surface or ground water. Moreover, the availability is secured under conditions by which the water temperature lowers to just above the freezing point. District heating systems have already been installed with an ice slurry generator (vacuum ice). Conventional heat pumps for district heating installations don't have a year round service. For instance in Sweden with the North Sea as energy source, the heat pumps have to be shut down in winter time to prevent evaporator freezing. Heat pumps working with an ice slurry don't meet this problem. These systems drain the formed ice into nearby open water, or into with ice covered water. In the last case the discharge system must be carefully designed to avoid ice jams [20, 25, 35].

According to interviewed companies a possible application can be schools, douches using hot water, air-conditioning using the cold energy. No special technology is necessary, only that the heat demand governs the kind and size of the storage tank and not the cooling load [A, C].

3.2.3 Separation/concentration

Desalination of seawater to obtain potable water is an important objective of ice slurry generation. The nearly pure water crystals formed in the ice slurry can be washed and further processed. This method can also be used for purification of water.

Concentration of solutions including juices, maple syrup or the concentration of waste can also be performed by ice slurry generation. Water is extracted from the original solution/mixture for the building of ice crystals. Freeze concentration of juice etc. is known and widely used technology (also beer, wine, black liquor, pulp).

Separation/concentration of mixtures like oil/water, is based on the same principle. This application is new and patented [C].

3.3 Global application/users

Three global applications have been distinguished. These global applications, storage, transport and heat transfer, are explained in the following paragraphs. In this context heat transfer is meant as being the eventual process of applying cold energy for maintaining or reaching a certain (product) low temperature. Generally, the applications storage and transport are used in combination with the application heat transfer.

A slightly other division into two global applications is possible as well [C].

- a. Slurry ice is either used as secondary refrigerant (energy density), i.e. as transport medium and/or used as storage medium.
 - b. Consumption/heat transfer means 'harvesting' ice from the icemaker for e.g. immersion cooling of products.
- a. and b. have different backgrounds. Whereas a. is competing with chilled water, brine or evaporating refrigerant, b. is competing mainly with ice makers and to some extent with chilled water. Under a. the enthalpy prevails and under b. the heat transfer is the important issue.

3.3.1 Storage

The storage of cold energy in the form of an ice slurry has not only the advantages of storing latent energy but also the advantages of transport and use of latent energy. No heat transfer (heat exchanger) is necessary between the storage medium and the working fluid. Conventional ice storage systems uses chilled water or an secondary refrigerant in direct or indirect contact with ice, as working fluid for transport and for heat transfer to the users.

Ice slurries can be generated and stored at a range of temperatures. Other storage media operating below 0 °C make use of sensible energy and lack the advantages connected with latent energy.

The meaningfulness of storage, in particular with regard to cost reduction, is determined by a number of factors. Examples of factors are the electricity rates, high / low rate, the maximum capacity which can be installed; the demand of cooling, seldom, continuously, big variations, base load etc.; legal requirements and restrictions.

Applications can be found in the air-conditioning systems, in food processing and refrigeration systems like breweries, dairy industry, meat processing, in discontinuous processes, when energy use is maximised, in district cooling etc.

In Japan more and more office buildings are provided with ice slurry (water and alcohol or salt) storage systems.

[1, 13, 19]

3.3.2 Transport

The good transport characteristics make ice slurries very suitable for a number of applications where the transport aspects form an essential aspect. District cooling is an important application in this respect.. The actual piping network is the single most expensive element in many district cooling systems. Ice slurry technology represents a method for reducing the mass flow rate for the same cooling capacity. The lower mass flow translates directly into smaller pipes and lower distribution system costs. Compared to a water supply at 7 °C, a 20% fraction ice slurry can reduce the pipeline diameter by more than a half.

Many options are available for pumping equipment. Both fine ice slurries and coarse fresh water slurries have been successfully handled using centrifugal or positive displacement pumps. In general, for positive displacement designs, no change in flow rates and minimal changes in power are expected. In the case of centrifugal designs, nominal changes in both flow and power consumption should be expected.

Operation strategies have to be developed to avoid having to restart the flow of ice slurry during normal operations. When an ice slurry is allowed to come to rest, the normally uniform mixture begins to stratify due to density differences between the ice crystals and surrounding fluid. The degree of stratification is strongly dependent upon ice crystal size. For most systems in which the distribution ice fraction is in the range of 20 to 30% little or no packing would be expected with a loss of flow. However, unforeseen circumstances, like pump or power failure, may still cause a shut down of the distribution system in the fully charged condition. Measures have to be taken to minimise the problem.

Whether it is more cost effective to use just the latent heat part of the ice slurry or a combination of latent and sensible heat depends on the situation. An optimum has to be found with regard to the transport and the heat transfer characteristics. Is emphasis put on the transport characteristics, large distribution network and relatively small number of heat exchangers, the smallest pipe diameter and therefore smallest investment costs, will be chosen. This includes an operation strategy making use of latent and sensible heat of the ice slurry. Is emphasis put on the heat

transfer characteristics, transport distances small compared to the large number of heat exchangers, the highest temperature difference for heat transfer minimising the costs for heat transfer surfaces, will be chosen. This includes an operating strategy making use of mainly the latent heat of the ice slurry.

The good transport characteristics make it possible to place the refrigeration installation in a larger distance to the user. This gives the opportunity to use 'hazardous' natural refrigerants like ammonia and hydrocarbons in a safe manner. [1, 16, 19]

3.3.3 Heat transfer

The heat transfer coefficient of an ice slurry is much better than that of water or even a boiling refrigerant. So it is not only an ideal replacement for indirect cooling with secondary refrigerants but for direct cooling with a refrigerant as well. Smaller heat exchangers than normally used for indirect cooling can be applied. It is even possible, to use existing evaporators of conventional refrigeration plants and replace the refrigerant by ice slurry in a retrofit case.

Retrofitting of existing installations (indirect cooling) with insufficient installed capacity or pipework with inadequate diameters, can be carried out by replacing the evaporator by ice generators, resulting in an increased plant capacity and cold energy transport capacity.

Direct contact refrigeration

The ice slurry is directly used to cool or freeze the products. Applications can be found in the cooling/freezing of fish (on board), in the cooling of agricultural products etc. Food containing salt by nature can be cooled directly by an water/salt ice slurry. The cooling of fish by an ice slurry prepared with the seawater the fish was caught from, is an example. Especially in Japan, Canada, Norway and Iceland many fishing-boats are equipped with ice slurry systems. The same holds for salmon processing plants. The salmon is precooled after killing and can be cooled once again before packing in transport cases.

Fish can be cooled on board a ship either by spraying ice directly thereon or by immersing the fish in a vessel, depending on the type of fish.

Depending on the specific processing or product requirements ice slurries can be used instead of conventional crushed ice for applications around 0 °C. The cooling velocity is very high and allows to chill or even freeze products within few minutes. Just caught fish is minutes cooled down from 12 °C to 0 °C. much faster than conventional cooling systems like RSW (Refrigerated Sea Water) or ice (flake, plate, scale). Herewith the growth of bacteria is strongly reduced. Due to the close packing of the ice crystals an ice slurry holds for a longer time than conventional crushed ice because of the lack of air interspaces. Experiments in Norway with the cooling of fish show cooling down times to the desired 0 °C of 120 minutes with chilled seawater and 58 minutes with an ice slurry produced of

seawater. Also the quality of the product increases by using an ice slurry instead of hard ice because of the fact that the skin is not damaged.

Sensitive products such as vegetables or fruit must not be frozen at all. Down cooling experiments of food by immersion in a non-agitated ice slurry (FLO-ICE) show the following results. Freshly harvested broccoli, whole heads in harvesting cases, cools down from 25 to 0 °C in 10 minutes. Pork-cutlet in jelly, packed in PE-box, cools down from 37 to 1 °C in 10 minutes. Vacuum packed salami-style sausage (d=60 mm, l=75 mm, g=192 g), cools down from 96 to 0 °C in about 60 minutes. At no time the products were suffering from temperatures below their freezing points.

Not only in the food processing but also in other industries like steel processing, direct cooling (immersion baths) with ice slurries can be applied.

Indirect contact refrigeration

The ice slurry is indirectly used as a secondary refrigerant in the heat transfer equipment.

Applications can be found in air-conditioning plants, in industrial process cooling (gas cooling, liquid cooling, liquefaction of solvents, condensation mine cooling etc.), in food processing, in commercial cooling, both refrigerated cabinets and frozen food cabinets, in cold stores, cooling of juices and beverages etc.

An example is given for an air-conditioning plant of an office building. For a maximum cooling load of 300 kW only 73 kW has to be installed with an adequate ice-storage of 25 m³ (FLO-ICE). The design and engineering of supermarket cooling with ice slurry is somehow different to conventional systems. The ice concentration must be high enough to allow for the full benefit of ice and therefore the conventional cabinets for direct expansion are basically better.

As already mentioned in paragraph 3.3.2, transport, a distinction can be made depending on whether high heat transfer or reduced pump volume is desired, e.g. high heat transfer for better use of 'evaporator' surface versus reduced pump volume for efficiency [E].

Ice harvesting

The ice slurry is transformed into dry, high concentrated 'conventional' ice. The ice can be used in the usual way for instance for packing of fish, displays etc., for industrial applications, for concrete cooling, for food (meat) processing etc.

In a storage tank the ice crystals float to the upper part due to the density difference between crystals and water/alcohol or water/salt solutions. In the upper part almost pure ice is present. Recrystallisation of the ice takes place, these ice crystals (up to 4 mm) are harvested and stored in another tank. The dry recrystallised ice can be used for instance for the cooling of vegetables (broccoli). In this case the tank is primarily used for the production and storage of dry 'conventional' ice and not for the storage of cold energy generated on the most cost and/or energy attractive way (see paragraph 3.3.3.1).

[1, 3, 71, 7, 13, 17, 16, 67]

3.3.4 User applications given by interviewed companies

The companies which filled in the questionnaire mentioned the following user applications of ice slurry:

Air cooling

Air conditioning and space cooling;

Air dehumidification systems;

Retrofit of plants with lack of cooling capacity, transport- and heat transfer performance;

Thermal storage systems (ice storage);

Commercial refrigeration:

Supermarkets;

Cold stores and cold rooms;

Food industry:

Quick cooling of fruits and vegetables after harvest;

Immersion cooling of fish after catch and/or slaughter

production ice out of fresh water or sea water,

capacity between 5 ton ice to 100 ton ice per 24 hours,

temperature ice $\geq -2,3$ °C (no freezing of fish);

Immersion cooling of packed food (e.g. bags after autoclave);

Meat industry (boning rooms, poultry cooling, hides, etc.);

Dairy industry (e.g. after pasteurisation, UHT-treatment), ice storage;

Breweries, beverage industry (also: concentration), ice storage;

Industrial applications:

Fish cooling (on board, on land, transport);

Cooling of tools, plastic industry;

Chemical processes requiring high cooling rates or removal of exothermic heat;

Compressed air drying;

Environmental applications:

Replacement of directly evaporating refrigerant;

Desalination;

Separation of oil/water mixtures.

Some further general remarks are:

Thermal Storage where widely ranging loads are encountered.

Maximal advantage is taken of the use of 'Off Peak' power tariff.

Air conditioning, food processing and initial cooling of fruit and vegetables, where high initial loads occur followed by low holding conditions.

Most attractive uses are applications where rapid cooling rate is required e.g. trawler, chemical plant, or where ice transport is desirable e.g. a ring motion in a factory.

4. Experience, realisations

According to the reviews a lot of installations working with different generation principles have been installed over the past years.

4.1 Vacuum crystallisation

Vacuum ice plants have been installed for mine cooling purposes in South Africa and Botswana, both single and two stage. Besides water, ammonia is sometimes used as refrigerant for the second stage. Cooling capacities are in the range of MW's.

Heat pumps with 2 * 18 MW cooling capacity have been installed in Germany. A vacuum ice plant is already put in operation for air-conditioning purposes. During some 120.000 hours of total operating time in about 4 à 5 years, no requirements for maintenance, service, spares or repair have been reported. Even under the worst conditions (chilling of untreated, polluted mine water in Africa) the plants are working well and did not suffer from decreasing efficiency due to fouling or scaling (company Integral).

[1, 2, 3, 5]

A pilot plant of a vacuum ice heat pump has been installed in Denmark for district heating. Seawater acts as heat source. The installation covers approximately 68% of the required annual total heat production, while the remaining 32% are produced by normal gas boilers. The system is well suited to be used under extreme ambient conditions, and is economically attractive under the conditions existing in Denmark [32].

4.2 Scraped surface heat exchanger

This type of installation has been installed for air-conditioning purposes, for commercial cooling, for cooling of products (fish, juices) etc. In [2] examples are given for an air-conditioning plant unit and for vegetable juice cooling plant (FLO-ICE). The cooling-down of vegetable juice from 25 °C to 5 °C takes 1 hour with conventional cooling with ice water (0 °C) and ¼ hour with ice slurry. It is very important to cool down as quick as possible to prevent the loss of flavours.

Tests have been carried out with supermarket chiller- and freezer cabinets (on a container of Greenpeace) originally designed for brine circulation. Distribution and storage of cooling was provided by a FLO-ICE plant. The refrigerant used was propane (Integral). Control is achieved by means of the simple built-in thermostat which shuts the cabinet off when the desired operating temperature is reached. The performance and the energy consumption were equal or even superior to conventional systems with direct expansion or indirect, brine using, systems. Brines were

used at a temperature of $-3\text{ }^{\circ}\text{C}$ (approximately 10% ethanol) for the chiller and some $-24\text{ }^{\circ}\text{C}$ (approximately 30% ethanol) for the freezer. The measured operating air-inlet temperatures were $-1\text{ }^{\circ}\text{C}$ and $-22\text{ }^{\circ}\text{C}$ (some 2 K difference between ice slurry and air), which is enough for standard operation [8, 16].

In a supermarket a pioneer installation for refrigeration purposes has been placed instead of a direct expansion installation. The ice slurry produced by three ice slurry generators (FLO-ICE), total capacity 35 kW, is pumped to a storage tank, provided with a stirring device. The ice slurry in the range of standard cooling is distributed by pumps over the users meat cabinets, dairy products, bakery products/vegetables and cold stores. The distribution system consists of plastic hoses, resulting in a simpler and faster assembling. Air temperature control is done by switching the fans on/off via thermostats. Tests showed that standard evaporators could be used as heat exchangers. R404A is used as refrigerant. The first experiences are positive. They show a higher driving energy consumption for evaporators and pumps than for a direct system, but reduction is possible. The energy for defrosting is significant lower because the heat exchangers hardly frost. The small temperature differences within the refrigerated spaces have a good effect on the quality of the refrigerated products [14].

Quite a number of commercial installations is in operation with this type of ice slurry (FLO-ICE) [16].

After performing field tests some 60 ice slurry systems (FLO-ICE) have been installed and are in operation in German speaking countries for about four years. The systems are used for air-conditioning in all kinds of office-buildings (industry, social, administrative etc.); in cold rooms of a butcher's shop in the temperature range from 0 to $6\text{ }^{\circ}\text{C}$, capacity 9 kW, refrigerant propane; supermarket cooling, chilled cabinets with an installed capacity up to 45 kW pro supermarket; office air-conditioning by adiabatic refrigeration and additional cooling with an ice slurry installation with a 33 kW capacity; cooling of juice with an installed capacity of 88 kW, storage volume 120 m^3 , propane as refrigerant [18].

In a supermarket in Norway, no problems were encountered by the change over of the existing installations, chilled cabinets and piping, from a direct expansion system to an ice slurry system [FLO-ICE] [30].

A summary of a number of present user applications of FLO-ICE is given below:

- Refrigeration in the supermarket

Ice slurry consisting of a 10% commercially available ethanol mixture with a maximal ice concentration of approximately 30%. The slurry is transported to the users where the ice concentration reduces to 0%. Higher ice concentrations are hardly applied.

Applications for example in Switzerland, Norway, Belgium and Greenpeace truck (also freezing).

- Refrigeration of fish
Direct contact cooling of fish with an ice slurry produced from sea water (2 - 3% NaCl and other dissolved salts) on board of ships and on land based installations.
Applications for example in Norway, Iceland, South Africa.
- Comfort air-conditioning
Ice slurry is produced from ethanol (10%) mixture with a very high ice concentration and stored in a storage vessel. The water present (+ ethanol) is circulated to and from the users.
Application for example in Germany.
- Separation oil - water
NaCl (4%) is added to a fluid consisting from water with waste, oil. Ice slurry is produced from this mixture, making use of the difference of density between ice and solution. By collecting the ice in a vertical tube almost pure water (ice) and a high concentration waste is obtained.
Application for example in Germany.
- Heat pump
The condenser of the ice slurry installation is used to produce hot water for showers. In the future the ice slurry will be used to cool the rooms.
Application for example in Switzerland.

In the past problems were encountered with glycol solutions. During a period of some years the many phase changes resulted in clotting of the glycol and with that the building of ice on the inside of the drum. The quality of the solution did not remain constant and glycol solutions are no longer used in the FLO-ICE system [A]. Tests for supermarket applications showed that the liquid injection of the refrigerant in the drum is critical.

Recently a new type of scraper has been developed, patented by Star Refrigeration. This scraper functions much better than the old type. The first plant with a larger drum (and new scraper) was installed in a fish factory. Other projects include a trawler and a chemical plant (pigment).

In Japan a combined district heating and cooling system has been installed. The system uses both ice and water storage. 14% of the peak summer cooling load is provided through ice storage. Water from the water storage tank is passed through a heat exchanger by the flow of the ice storage loop. The ice generator/heat pump system(2,5 MW) has a COP in icemaking equal 2,4. Benefits come from reductions in installed capacity, operating manpower and from shifting a portion of the load to off peak times.

Also a pilot plant of 908 ton/day ice making capacity for deep mine cooling is in operation in Japan. The working areas are 3 to 4 km below surface. The reduction in pumping costs by pumping ice slurry to the working area is the major benefit [21] (scraped surface system, Sunwell).

4.3 Binary solution

A dozen of (internal turbulator system, MaximICE, Mueller Company) systems have been installed to date. The most common applications have been on dairy farms, although several systems are being used in process cooling and HVAC applications. One unit was examined after 4500 hours of operation, with no changes noted in either tube wall or rod thickness. The rod drive assembly, featuring a small electric motor and a drive plate, is simple, reliable, and accessible for maintenance. The manufacturer estimates a 20-year service life for the drive plate, although the main crank bearing might need replacement every year or two. The manufacturer's own comparison to a 200-ton ice harvester shows that the slurry systems uses 93% less heat transfer surface, 20% less power, has a 30% lower evaporator cost, 60% smaller footprint, and 75% less design operating weight. The design day performance of the system has been about 0,9 to 1,1 kW per ton.

4.4 Ice layers/flakes

A test facility has been built to improve the liquid icing for precooling broccoli or for root vegetables, artichokes, brussels sprouts, green onions, leeks, peas, some melons, and sweet corn. The system consists of a continuous ice feeding system without a reservoir for ice-water mixing. The power requirement is less than for the conventional system because no pump for an uniform mixture is needed and no batches to maintain a constant ice-water ratio. The ice-water slush is used immediately after ice and water are mixed. From the flaker the ice goes through the storage room, the auger, the crusher, the crushed ice reservoir, the ice-water mixing chamber, the diaphragm pump, the injection and control handle, and the box of products to be cooled [56].

5. Investigation of technical and marketing requirements

To get insight into the needs for the introduction of ice slurry on a larger scale than so far has been realised the most important factors concerning ice slurry have been put in line. These factors deal with both technical as marketing aspects. The present situation, which advantages and disadvantages related to the ice slurry technology, which market segments involved, which type of applications realised, which problems related to the generation technology or to the properties of ice slurry encountered, which parties involved, which introduction hurdles experienced, which marketing policies and sales networks present, is shortly described in the following paragraphs. The requirements for a market breakthrough are indicated as well. The former chapters already memorise the possible users/markets, the experiences with and the realisations of commercially available ice slurry systems, with vacuum ice and scraped surface ice as the most important technologies. In Europe the emphasis lies on FLO-ICE (scraped surface) systems.

5.1 Integral aspects ice slurries

The strengths and weaknesses of the ice slurry technology, and in particular FLO-ICE, can be summarised as follows [0]:

Strengths:

- Ice slurry is a natural alternative for the CFC/HCFC problems (ODP, GWP) by using NH_3 or other environmentally benign fluids
- Ice slurry can consist of natural ingredients (water + addition), so environmentally benign, commonly used solutions are water/ethanol/inhibitor (minimal 10% ethanol by mass), water/NaCl (minimal 4% NaCl by mass) and sea-water;
- The ice slurry principle is a kind of indirect refrigeration system, so less refrigerant is needed in the primary circuit, reducing ODP and GWP;
- Application possibilities for both refrigeration and freezing (future, defrosting problems);
- Large heat capacity due to the latent heat of the ice crystals;
- Storage during a long period is possible, for instance to meet peak loads, to use cheaper electricity tariffs and to use low condensing temperatures;
- Possibility to retrofit in existing installations;
- Reduction of the installed capacity because of storage opportunities ice slurry;
- Safe in the case of leakage, hardly influence on the quality of products;
- Hardly release of smell at lower temperatures (vapour pressure curve);
- Possibility to apply natural working fluids, like ammonia or propane, in the primary circuit;
- Application in risky situations, for instance a lot of people present or refrigeration of expensive products etc.;

- Possibility of direct contact cooling of product by ice slurry, dependent on melting-point depressive substance.

Weaknesses

- At present the costs per kW of a cylindrical scraped heat exchanger compared to conventional heat exchangers are high, a storage tank, if applicable, is an investment cost raising item;
- At present, only relatively small capacity (to about 10 à 12 kW per unit) cylindrical scraped heat exchangers are available;
- In particular at higher temperatures ($T > 0\text{ }^{\circ}\text{C}$) the ethanol present, escapes faster than water because of the difference in vapour pressure (indirect systems);
- Much room required for installation, especially for the storage vessel, if present;
- Temperature ice slurry always below $0\text{ }^{\circ}\text{C}$ when ice crystallises out of the solution;
- At the increase of the ice concentration the temperature lowers;
- Simple technology (possibilities for imitation);
- Little functional data known of existing, commercially installed installations;
- Education/training necessary for maintenance and installation personnel to handle the ice slurry installation;
- Natural resistance for a new technology from the existing refrigeration installation world;
- Separation occurs during the storage of ice slurry. A mixing device is essential to keep the solution homogeneous;
- Because of the mechanical components in the scraped heat exchanger, maintenance is very likely.

5.2 Energy savings and environmental benefits

Energy savings

With respect to energy consumption of an indirect contact ice slurry system, a theoretical calculation has been made based on some practical figures [0]. The energetic comparison has been carried out for a standard application in a supermarket (three refrigerated cabinets, refrigerating capacity maximal 40 kW, average 22 kW). The comparison holds for the systems:

- *indirect FLO-ICE cooling system,*

Including ice storage, producing of ice during the hours with the lowest ambient temperature is the most energetic favourable way. The average condensing temperature is 15 °C (5 °C (ambient temperature) + 10 K (assumed difference between condensing and ambient temperature)). The assumption is that no condensing pressure control is necessary because of the low condensing temperature.

FLO-ICE is produced with an ice concentration between 0% and 20%. Corresponding temperatures are -4,4 °C and -5,9 °C. The average evaporating temperature will be -11 °C.

Configuration system: compressor, condenser, thermostatic expansion valve, scraped heat exchanger, user, pump from scraped heat exchanger to storage vessel or user, pump from user to storage vessel or scraped heat exchanger, scraper motor, storage vessel and stirring device, piping (100 m). The storage vessel is meant for loading during 14 hours and unloading during 10 hours. The secondary refrigerant is a commercially water/10% ethanol/inhibitor mixture.

- *direct expansion system (DX),*

Field data showed a condensing temperature of 30 °C (20 °C + 10 K) as being realistic if the cooling takes place more during high ambient temperatures and not as an average during 24 hours. The evaporating temperature is -11 °C.

Configuration system: compressor, condenser, thermostatic expansion valve, user (evaporator), piping (100 m).

- *indirect brine system,*

The average condensing temperature is 22 °C (12 °C as average ambient temperature + 10 K). A storage vessel is used with accumulating capacity.

Because of the desired temperature of -8 °C at the users, and the loss (raise in temperature in the transport net due to presence of only sensible heat) the evaporation temperature has to be adapted to the demand. Assumed is an average evaporation temperature of -14 °C.

Configuration system: compressor, condenser, thermostatic expansion valve, heat exchanger (evaporator), user, pump in secondary circuit, piping (100 m).

The secondary refrigerant is propylene glycol.

The primary refrigerant for all three systems is R22.

The results of the calculation are presented in the table below.

	FLO-ICE	DX	Brine
maximal refrigerating capacity user [kW]	40	40	40
average refrigerating capacity user [kW]	22	22	22
total required refrigerating capacity [kW]	42,345	40,608	42,164
condensing temperature [°C]	15	30	22
evaporating temperature [°C]	-11	-11	-14
<i>energy consumption:</i> <i>[kWh/reference year]</i>			
compressor	69989	122664	102599
pumps	4450		10301
stirring device	4792		
scraper motor	2978		
total	82209	122664	112900
related to DX system [%]	67	100	92

In the mean time, practical experience learned that the energy consumption of an ice slurry system in the above mentioned application is between 80% to 90% of the energy consumption of a direct expansion system. The difference with the calculated value is mainly caused by a higher average condensing temperature in practice and by a slightly different loading and unloading pattern of the storage vessel. In contrary to the assumption the system works not only during night time (low condensing temperature) but sometimes also during day time (higher condensing temperature).

Based on these results and other practical experience, in optimised systems energy savings of 10 to 20% are expected for most of the other FLO-ICE applications.

Environmental benefits

Environmental benefits can be gained by the application of natural working fluids instead of CFC's or HCFC's as primary refrigerant in ice slurry systems. The safety aspects related with natural working fluids like ammonia (toxicity) and hydrocarbons (flammability) can be dealt with by the application of ice slurry as secondary refrigerant. Due to the good transport properties of ice slurry, the refrigeration installation including all primary refrigerant containing parts, can be located at a safe distance from the user. In this way the opportunity is created to take all necessary safety provisions and measures, and to comply with (provisional) safety regulations. Furthermore the amount of primary refrigerant is restricted to the minimum.

In most cases replacing a direct expansion system using a CFC or HCFC by an ice slurry system with the same primary refrigerant is an environmentally improved option, because of the lower primary refrigerant contents.

With respect to the ice slurry media, the ice slurry secondary refrigerant system is inherently environmentally benign, depending on the ice slurry media used (water, ethanol, NaCl, etc.).

5.3 Present situation refrigeration branch

The installers form the actual heart of the refrigeration branch [0] and are a very important player in the field of introduction ice slurry technology.

This branch shows a large diversity, both in size and in working area. About the half of the total group installers consists of very small enterprises (10 employees or less). The smaller installers hardly follow a certain strategy. They are a kind of generalist, often exclusively active in the field of the smaller refrigeration technology with a big spreading in customers, characterised by ad hoc management. However, they are much more flexible than their bigger brothers and usually, they do have good personal relationships with their local customers. A number of medium and larger installers follow a differentiation strategy, for instance by extension of the product assortment. Of utmost importance, herewith, are the aspects reliability, quality and service. The costs and the know-how play important roles as well. The greater part of the installers deal with several market segments. Due to their size almost all large projects can only be carried out by the larger installers. The smaller companies are mostly regional active, the medium companies national and sometimes international, the larger enterprises operate both nationally and internationally.

The competition is strong in this branch of industry. Because most customers want a fast, good and reliable service, only possible if the installer is located on reasonable distance, the competition is focused on regional and national level. Service and maintenance activities are very important to installers, not only to distinguished themselves from others but also because these activities are much more profitable than new building. On the other hand the extent of the turnover of new building is much bigger than of service and maintenance. Especially for the largest installers the greatest part of the turnover (about 80%) comes from new building and only a very small percentage from service and maintenance.

In general the installers are not very creative and innovative. This implies that almost always use is made of well-tried concepts, both commercial and technical. Often this group is strongly focused on products and production with less attention for the needs of (potential) customers. Until now marketing is not very common in the refrigeration branch.

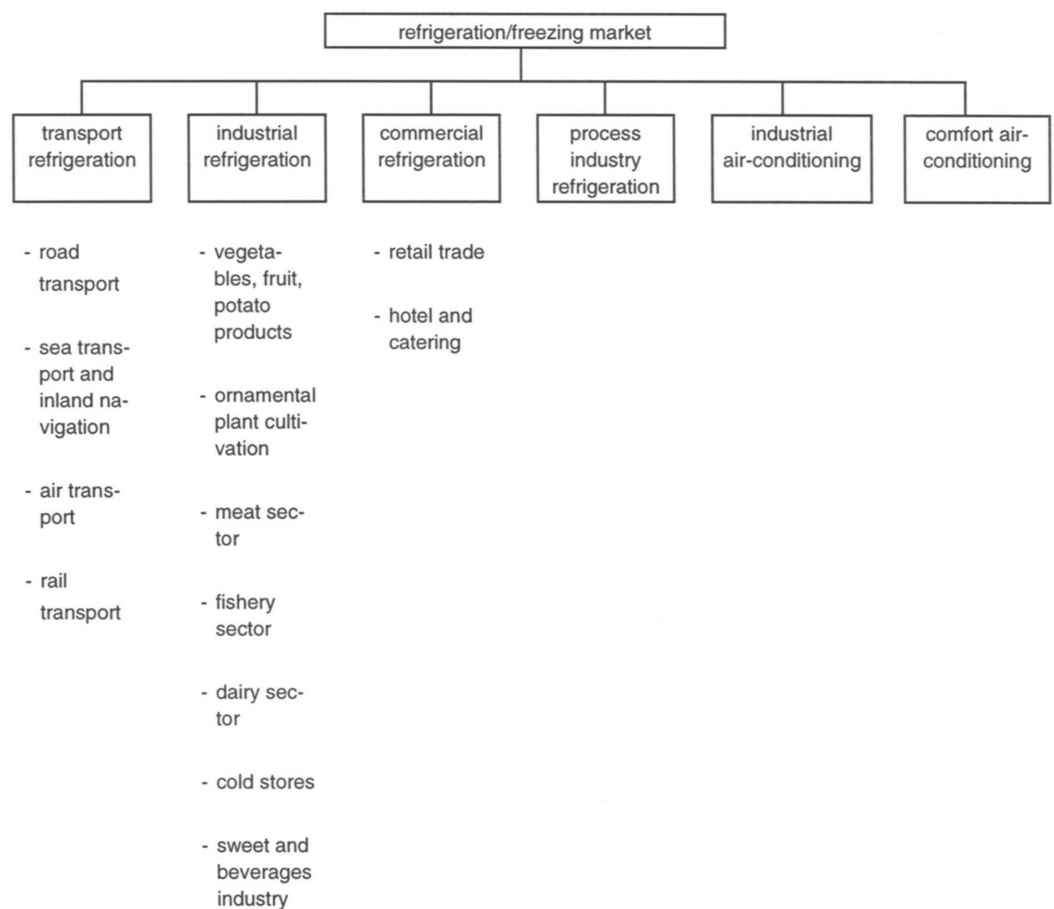
Only a relatively small number of suppliers of refrigeration components does exist. Usually the components in question are standard products, produced in series. The price at purchase is very significant because all installers can fulfil about equally the important requirements concerning quality and a short delivery time. International there is an increasing trend in concentration of manufacturers of components, resulting in a number of powerful companies. Manufacturers and installers depend strongly on each other. In the next few years world-wide a further scaling up will take place for manufacturers.

The customers mainly originate from the market segments transport refrigeration, industrial refrigeration, commercial refrigeration, process industry refrigeration, industrial air-conditioning and comfort air-conditioning.

New impulses to the branch have been given because of the environmental problems and energy savings to obtain more efficient and environmentally benign installations. The ice slurry technology belongs to the new substitutes.

5.4 Market aspects

The most important market segments of the (Dutch) refrigerating market can be differentiated into a number of sub-markets [0].



A characterisation of the market segments with their opportunities and threats, is given in the following. Although the Dutch situation acts as starting point, most of the descriptions have a more general nature.

Transport refrigeration

In the road transport sector small DX systems with R22 or R134a are used. Ships also use DX systems or indirect systems with brine.

Opportunities

- expansion of international refrigeration transport;
- future stronger requirements qua cooling capacity, humidity control, space usage;
- environmental legislation, existing and new installations;
- scale-up and concentration of transport enterprises.

Threats

- over-capacity conditioned transport in the Netherlands;
- international competition.

Industrial refrigeration

The auctions for vegetables, fruit and potatoes normally use ammonia pump systems. Storage of cold with the aid of ice banks.

The auctions of flowers use in principal DX systems.

Within the EC the Netherlands are the biggest exporter of meat. Within the meat sector a number of changes like concentration of companies, shift of slaughtering activities to the industrial sector, criticality of the consumer, takes place. Usually central ammonia systems are applied in slaughterhouses. Use is made of DX systems (mainly R22) as well.

The fishery sector is increasing. The activities show a shift from the catching to the handling of fish. Coasters use crushed ice, produced on board, for the cooling of the fish. Also DX systems are present for refrigeration. Ships for the more 'distant' fishery have refrigerated sea water cooling systems, but also freezing installations (R22 pumping system). Also vertical plate freezers and storage rooms operating with indirect systems with calciumchloride brine are present. The fish processing industry uses DX systems (CFK's, HCFC's), brine systems or cryogenic refrigeration with nitrogen. The wholesale trade has cold stores working with DX or brine systems.

In the dairy sector much use is made of heat exchangers at a temperature level of about 0 °C, produced by ammonia pump systems and indirect brine systems. Depending on the product there is a trend for an increasing market. A by taking over smaller number of, but more powerful, companies has a very active policy in the development of new products. The new products mean other requirements for the refrigeration means.

In the near future expansion of the storage capacity of cold stores in the Netherlands is foreseen.

The few Dutch companies active in the sweets and beverages sector use DX systems or pump systems with R22 as working fluid.

Opportunities

- more rigid legislation and inspection of the cooling of products;
- strong international position of the Dutch vegetables, fruit and flowers and meat sector;
- vertical integration public cold stores;
- increase assortment chilled products;
- increase consumption chilled and frozen foods;
- environmental legislation;
- concentration and scaling up of customers.

Threats

- shift added value from installation company small parts to producer of standard sets;
- over-capacity meat sector;
- reduction EC intervention stocks;
- fishing quota;
- impending over-capacity public cold stores.

Commercial refrigeration

The detail trade is strongly subject to changes resulting in less but more powerful parties in the distribution to the final consumer. In this manner very strong requirements could be posed to suppliers of refrigeration installations. Also higher demands are made upon refrigerated cabinets because of the wish to increase in assortment of products and because of the wish to raise the product quality. The retail trade uses mainly direct expansion systems (R22). Due to environmental problems caused by the use of traditional refrigerants, a shift towards indirect systems is observable.

The hotel and catering sector uses mainly direct expansion systems with small capacities. A positive sales potential is foreseen.

Opportunities

- more rigid legislation and inspection of chilled products;
- increase consumption chilled and frozen foods;
- environmental legislation;
- public opinion;
- scaling-up retail trade.

Threats

- increase international competition.

Process industry refrigeration

This sector is dominated by big enterprises in the chemical industry. Usually the refrigeration installation is part of a complete process.

Opportunities

- more rigid legislation;
- growth of the market segment;
- energy savings.

Threats

- increase competition.

Industrial air-conditioning

A main part of this sector is formed by vegetable growers. Use is made of large pump and direct expansion systems with R22 as working fluid.

Opportunities

- environmental legislation.

Threats

- international competition.

Comfort air-conditioning

Globally the systems for this category can be divided into central and decentral systems.

Opportunities

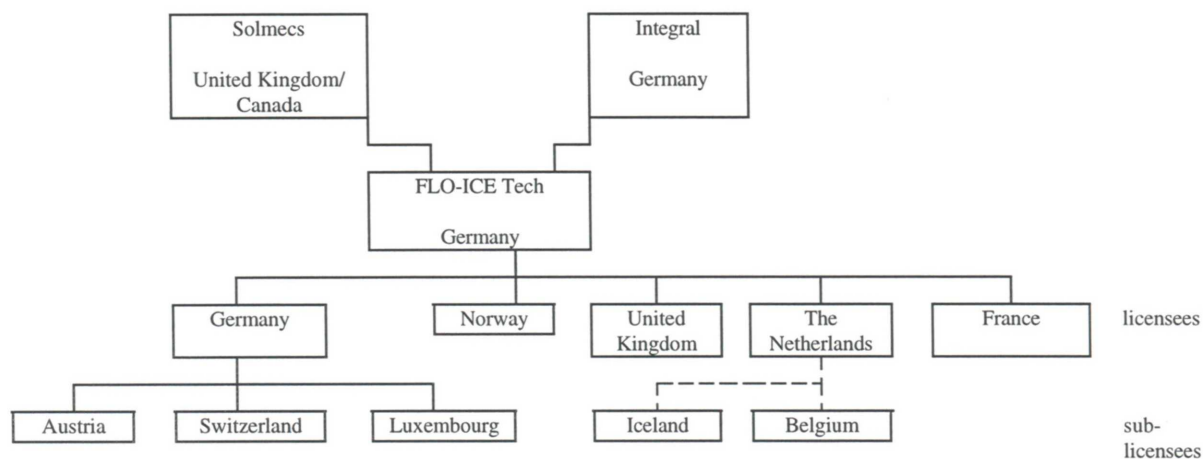
- energy savings;
- environmental legislation;
- increase cooling demand.

Threats

- international competition.

5.5 Present situation FLO-ICE network

The original Russian idea of a scraped heat exchanger has been developed into a concrete product by the companies Solmecs FLO-ICE Systems Limited in co-operation with Integral Energie Technik GmbH. These two companies set up the company FLO-ICE Tech GmbH to take care of the interests of the licensees. The distribution network of means and knowledge is presented in the tree scheme below.



The licensees and sub-licensees are included in appendix C.

5.6 Requirements users/market segments

The requirements of the users concerning refrigeration technology, and especially ice slurry technology, have a various nature. The requirements concern aspects as temperature, refrigerating capacity (latent and /or sensible heat), legal requirements, product quality, costs both investment and running costs (energy consumption, maintenance etc.), reliability, etc.

Dependent on the application of the ice slurry, use will be made of just the latent heat or an combination of latent heat and a part sensible heat. For indirect systems an optimum has to be found for the enthalpy of the slurry and the pipe diameter of the distribution system. In this respect, usual values for operation characteristics of ice slurries in a number of application fields are given in the following table [30]:

application	range slurry temp. difference [K]	ice concentration [%]	medium in system (pipes and heat exchangers)
supermarket	0	10 - 20	ice slurry
air-conditioning	0 - 5	15 - 25	ice slurry
ice storage for air- conditioning	0 - 12	50 - 70	ice water
district cooling	15 - 20	20 - 35	ice slurry

According to the companies which completed the questionnaire, various user requirements play an important role in the introduction and/or application of ice slurries in a number of market segments.

The companies have practical experience with ice slurry in the market segments commercial refrigeration: supermarkets, cold rooms; industrial refrigeration: fishing sector, vegetables (hydro cooling), beverages (soft drink concentrates); process industry refrigeration: chemical; comfort air-conditioning ; building services. Other applications of this type of ice slurry are included in paragraph 4.2.

For the above mentioned applications ice slurry generated by the scraped heat exchanger methodology can be applied for the lower capacities with temperature down to -40 °C using salt, sugar or alcohol solutions. Vacuum ice can be used for larger capacities, above 200 kW at approximately 0 °C with water having a small amount of impurities. At the moment direct contact cooling is only possible with NaCl ice. Ice slurry with a minimum salt content is only possible with vacuum ice or with the aid of the recently developed larger drum/new scraper heat exchanger. For supermarkets : indirect systems, capacity up to 100 kW, cooling: temperature - 4 °C/-5 °C, peak shaving, both retrofit and new.

For the fishing sector: direct contact, 2,5 - 5,0 - 7,5 ton ice per 24 hours for freeze trawlers, ≥ 100 ton ice per 24 hours for fresh fish, temperature range -1,9 °C to - 2,5 °C, no freezing of fish, all new.

Other promising market segments are low temperature applications for cold stores, merchant ships, supermarkets etc. in compact sizes up to 250 kW. The preservation of animal skins and the replacement of CFCs in existing installations are also be

considered as promising market segments.

An important requirement concerns the safety of the medium. It has to be low toxic, at least not harmful to foodstuffs, preferably non toxic, and environmentally friendly.

The primary refrigerant must be kept to a minimum.

The installation has to be reliable and easy to maintain. The performance (C.O.P.) has to be at least comparable to primary refrigerant systems.

The benefits of the use of ice slurries as experienced by the companies are:

- the rapid cooling of products (direct contact) resulting in better quality,
- energy savings,
- small pipes,
- major pipework easy to install, with no specialised labour,
- low pumping power,
- low installed capacity,
- small storage,
- high heat transfer,
- high energy density,
- no (little) emissions,
- transport properties,
- reducing bottlenecks in processes,
- less primary refrigerant,
- new solutions to old problems e.g. the melt rate in traditional thermal store ice banks.

Problems and hurdles for introduction encountered are:

- use of ice slurries for lower temperatures down to -40 °C, the technical requirements will need to be satisfied with on-site tests,
- capacity of the original scraped heat exchanger too small for some applications,
- scraped flat plate heat exchanger for larger capacities is not yet a commercial product,
- the investment costs of scraped heat exchangers are relatively high,
- the performance, overall C.O.P. decreases by application of a HFC instead of R22 as primary refrigerant due to a worse heat transfer,
- keeping the medium, water/alcohol mixture, in a good shape,
- additive in the solution, for direct cooling applications,
- problems with the freezing-up of evaporators and the control of ice concentration are solved,
- the design of the mechanical parts of the ice scraper mechanism is improved,

Some general hurdles for the introduction of a new technology are:

- general acceptance of a new, not yet proven or familiar, technology,
- acceptance by multinational and/or large companies of a technology from a small company,
- education/training of users and installers
- the lack of user experience, experience of actual installations, too less reference plants.

Stimuli for the introduction can be found in:

- the realisation of ice slurry installations with a wide variety of applications which gives market confidence,
- the realisation of co-operation with suppliers of refrigeration equipment/installers,
- the propagation of the benefits of the use of ice slurries, by publications, seminars, conferences, information to installers, to industrial organisations, user groups etc.,
- the solving of the problems and hurdles already mentioned,
- training and education programs,
- legal and/or user requirements, like the use of refrigerants, rapid chilling of products, energy savings etc.,
- support from universities and research institutes.

Besides the suppliers of ice slurry technology a number of other parties are involved in the market introduction. Activities developed and to be developed by the suppliers have to be supported and picked up by the other players. Some of the hurdles and stimuli mentioned before have to be (partly) dealt by other parties than the ones directly interested.

It is crucial to develop ways of demonstrating the advantages of ice slurry technology to managers (end users/installers), one of the players in the field of market introduction. This must be done in connection with the primary concerns of management, which are finance and continuity: a process has to be profitable and has to function properly. Thus, the key issues to be addressed are the misconception that ice slurry technology makes it more expensive and conservatism ('it might not work'). As already indicated, demonstrating the value of ice slurry technology should be done through real-world examples: these are the most successful in convincing people. Furthermore, examples should not only deal with new situations, but also with existing plants. Co-operation with industry on real-world examples will not only be meaningful for presenting them for wider use but also for gathering information.

At this point it is appropriate to discuss shortly the role of the various other players in connection with ice slurry technology.

Regulatory authorities could play an indirect role in stimulating the adoption of ice slurry technology by issuing and/or promoting environmental regulations, energy saving programs etc. They could play a more active role by suggesting the use of

ice slurry technology in accompanying documents, at the European Community level as well as the national level.

Branch and user organisations can play an important role in spreading the possibilities of ice slurry technology, by discussing the topic, making it a subject in conferences and promoting research.

The contribution of the research community is very important in developing real-world examples as well as in making improvements and in finding solutions for (technical) problems.

5.7 Selected aspects

Based on the information included in the reviews and from bilateral consultations with licensees a number of technical and non technical aspects stand out which need further attention. For a real market breakthrough the selected aspects have to be in good order. Thus, further elaboration of the selected aspects is considered as a necessary condition for a wide spread introduction of ice slurry technology, and especially FLO-ICE and vacuum ice (Binary Ice).

Technical aspects:

- storage vessel, design and system integration;
- secondary refrigerant (solution), technical and health characteristics/limits of additives;
- further development of scraped heat exchanger with larger capacity;
- further development of vacuum ice plant with conventional refrigeration equipment;
- defrosting, freeze applications.

Non technical aspects:

- real world examples like full scale plants, demo's;
- price/performance relation;
- education, training courses/documentation for designers, manufacturers, installers, end-users;
- public relations;
- technology network including equipment suppliers, installers, end-users.

Furthermore, specific market segments and applications need their own technical and marketing approach.

6. Conclusions

The introduction of ice slurry technology makes a slow start. In a number of market segments specific applications of ice slurries are on their way and the possibilities for new applications are under continuous exploration. Sometimes technical problems hinder the use of ice slurry technology for certain users. But first of all, it is necessary to convince people of the benefits of ice slurry technology with respect to conventional refrigeration. To that end a structured marketing program is needed.

Just a few of the ice slurry generation principles have been developed into commercially available products. Most of the generation processes are still in the development stage or at most at the level of pilot plant. Commercially available technologies are mainly restricted to the scraped surface heat exchanger and to vacuum crystallisation. One of the main suppliers of scraped heat exchangers, and partly of vacuum ice installations, is Integral/Solmecs with their FLO-ICE network of licensees and sub-licensees.

The main conclusions are:

- Ice slurry technology, in particular FLO-ICE and Binary Ice, is technically feasible. However for a wide spread introduction of this technology some technical and non-technical aspects have to be assessed. In chapter 7 these aspects are described in more detail.
- Using ice slurry technologies, energy savings between 10 and 20% are expected in most applications for optimised systems.
- The applications of ice slurry technologies makes it possible to use natural refrigerants like ammonia and hydrocarbons as replacements for ozone depleting and/or global warming substances like CFCs, HCFCs and HFCs.
- Ice slurry technologies are economically feasible in future depending on the opportunities for a real market breakthrough. Technological developments and market penetration play an important role in this.

7. Recommendations and exploitation of results

The recommendations, to achieve a real market breakthrough of the ice slurry technology, concern the selected aspects, both technical and non technical (see paragraph 5.7). The recommendations indicate how the selected aspects can be dealt with, which approaches are proposed. The recommendations are couched in short project descriptions. For most of the projects proposed, support from EC-RTD programmes will significantly accelerate the market breakthrough of this beneficial technology.

Technical aspects:

- Storage vessel, design guideline
No guideline exist for the design of the storage vessel for ice slurry. Apart from the size of the vessel, the required characteristics of vessel and accompanying equipment have to be specified by a, more or less, trial and error method. Characteristics like the dimensioning of the stirring device, the way the ice slurry will be supplied by and returned to the ice slurry generator, the way the ice slurry will be supplied to and returned from the user(s), the ice concentration, the energy consumption etc. have to be modelled. The modelling has to comprise the flow pattern, the homogeneity of the ice slurry and the energy needed to maintain the situation, all dependent on equipment and ice slurry characteristics. After validation of the model a design guideline for the storage vessel (integrated in the system) can be drafted.
- Secondary refrigerant (solution), technical and health characteristics
Further research is needed to assess which additives in which concentration are applicable and allowed at which temperatures for direct or indirect use in ice slurries. The research has to include not only the freezing point depressives, but all kind of dopes as well (e.g. anti-corrosion). Especially in direct contact applications, the health aspects are extremely important. The behaviour of the water/addition/dope mixture at various temperatures has to be investigated. The long term behaviour, phase changes, and the evaporation of, for example alcohol, resulting in composition transformations, are issues for investigation as well. A survey of permitted media to be used without problems in which applications and at which temperature levels etc. is the result.

- Flat plate heat exchanger, development equipment
At the moment the scraped flat plate heat exchanger is in development (Integral). This type heat exchanger is meant as extension in capacity to the scraped drum, so a whole range of capacities comes available. The pilot scale apparatus has to be transformed into a commercial product. An European technology development project focused on the further equipment development can take care of a quick realisation of an cost-effective and energy saving scraped flat plate heat exchanger.
- Vacuum ice plant, development equipment and demonstration
At the moment a testing arrangement is being built and preliminary tests will be carried out. This type of vacuum ice plant, based on the sublimation of water vapour, and built with conventional refrigerating equipment, is meant as an capacity extension to the scraped drum for temperatures of approximately 0 °C. A strong support is needed to the further development of the test apparatus into a commercial product. In order to realise the commercialisation quickly a lot of effort has to be put in. The setting-up of a technology development project to that end, would be very supporting to achieve a cost-effective, environmentally friendly and energy saving vacuum ice plant. Thereupon the next step comprises the up-scaling and engineering of the present 50 kW compressor capacity installation to a 1 MW plant. With the co-operation of a potentially interested client a demo-project can be set up to gain practical experience with this type of plant.
- Freeze applications, defrosting
The problem of defrosting stands out particularly in freezer cabinets for commercial refrigeration. An evaluation of the possibilities, the advantages and disadvantages and of the experience with already installed freeze applications gives insight in the technologies, the control strategies, the technical problems to be expected etc. Eventually, the evaluation leads to an optimised defrosting qua energy consumption, performance, reliability etc.

Non technical aspects:

- Real world examples like full scale plants, demo's
To demonstrate the benefits of a new technology it is necessary to have full scale plants operating, preferably in several application fields. The practical ins and outs have to be experienced in the field. Possible specific application problems can be solved and improvements introduced. To that end real world applications have to be created. These examples need a careful support and attendance to get an independent observation of their performance and their advantages with respect to conventional refrigeration (corresponding to phase 4 of the original proposal, see chapter 1).

- **Price/performance relation**

The general assumption is that the ice slurry technology is too expensive. In the field of refrigeration decisions are usually made based on capital costs. An investigation of the capital and running costs (related to refrigerating capacity), and eventual of the whole life cycle costs, is necessary to have a solid base for comparison with conventional refrigeration systems. The performance can be characterised by a number of items, like product quality, environmentally friendliness, ease of operation, maintenance, reliability, imago user, etc. A decision analysis model can be drafted to value each of the characteristics into a total judgement. Dependent on the ice slurry technology used, the specific user and application a more objective decision can be made pro or against ice slurry.

Some general reference cases have to be defined to be subjected to the decision analysis model. If it turns out that in these reference cases ice slurry technologies are rejected because of their high overall costs, measures have to be taken to reduce the prices.
- **Education and training for designers, manufacturers, installers and end-users**

An European project has to be started for a comprehensive route of training and education to introduce the ice slurry technology into the market. A lot of activities like the drafting of documentation, including the technology into handbooks, organising training courses for several levels like mechanics, installers, including ice slurry technology in existing general, refrigerating courses and training have to be part of this route (corresponding to phase 3 of the original proposal, see chapter 1).
- **Public Relations**

To get the ice slurry technology well known, a PR programme has to be set up. The correct material has to be drawn up. Questions like, which groups have to be addressed with which message, who is addressing (single partner or FLO-ICE network as a whole etc.), which form/layout of the PR material etc. have to be answered.
- **Technology network**

To promote the possibilities of ice slurry technology, to exchange experiences and to explore possible new applications a structured users network is very useful. Activities of the network could comprise the issuing of newsletters, organising symposia, creating a kind of information ('help') desk etc. Such network can be initiated and co-ordinated for instance by the FLO-ICE consortium. Expansion of the network to ice slurry technology in a broader sense, including equipment suppliers and installers as well, can also be considered. An European technology network can be used as an incentive to concentrate European technologies to enter into competition with those outside Europe, to form a power, in particular to Asia and the States.

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Interviewed companies

- [A] see appendix B
- [B] see appendix B
- [C] see appendix B
- [D] see appendix B
- [E] see appendix B

9. Authentication

Name and address of the principal:

Commission of the European Communities
Directorate General XVII
200, Rue de la Loi
B-1049 BRUSSELS
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THERMIE Type-B actions
project: SME-0112-95-NL

Names and functions of the cooperators:

M. Verwoerd	- research worker, TNO
R.C.A. Smeets	- product manager, INHAM REFRIGERATION B.V.
R.J.M. van Gerwen	- head of the Department of Refrigeration and Heat Pump Technology, TNO

Names and establishments to which part of the research was put out to contract:

.....

Date upon which, or period in which, the research took place:

April 1996 - December 1996

Signature:



M. Verwoerd
research co-ordinator

Approved by:



Ir. R.J.M. van Gerwen
head of the Department of Refrigeration and
Heat Pump Technology

Appendix A Questionnaire

Questionnaire

1. General

Company

- Name:
- Profile:
- What are your main market segments?:

Person who filled in this questionnaire:

- Name:
- Function:
- What is your involvement in slurry ice activities? (sales, engineering, commissioning, service and maintenance, etc.)
- Are you working for 100% on slurry ice, or do you have other tasks to fulfil as well? What other tasks?

2. Generation of ice slurry (see also the scheme)

- The scheme indicates several ice generation processes. With which processes are you familiar?
- Are you aware of other generation processes, not mentioned in the scheme? Which ones?
- Can you describe the generation processes you are familiar with?
items such as:

- principle	- technical installation	- media used on the primary side
- composition of ice slurry	- ice production capacity [ton/24h]	- temperature range of the ice slurry
- status of the process (lab, prototype, pilot plant, commercially available,)	- estimated cost per installed kW (refrigeration capacity)	-

3. Purpose for generating ice slurry

- One or more of the above mentioned processes can be used for several purposes. One main purpose is to generate a ice slurry. This topic will be dealt with in the next questions. Other purposes could be:
 - as heat source for heat pumps
 - for separation or concentration objectives.

Are you familiar with these application purposes? Can you give us some information about these applications and/or do you know some other application purposes?

4. Global application of ice slurry

- Do you agree with the global division of the use of ice slurry into three main areas:
 - storage
 - transport
 - consumption?

Of course these three areas are not standing alone, but, dependent on the specific application, are connected to each other.

5. Users of slurry ice

- Can you describe the user applications of slurry ice? (see also the scheme)
- What is your experience with slurry ice applications?
- Which market segments?
- What are the specific technical requirements of the users in the indicated market segments?
items such as:
 - direct or indirect contact - capacity - temperature range
 - toxicity - new or retrofit - peak shaving
 - etc.
- Are the existing technical and commercial requirements sufficient? Why not?
- Which legal requirements have to be met or taken into account? (dependent on country and market segment).
- Are there any stimulating measures for introducing ice slurry applications and for what reason?

- Which generation process(es) is (are) suitable for the distinguished user applications? (see also question 2)
- What is the experience out of practice from installed ice slurry installations?
 - (solved) problems
 - benefits
 - pay back period
 - etc.
- What other market segments do you think are very promising for ice slurry (in general) applications? Market segments, where you don't have experience with ice slurry.
What are the reasons? (technical, marketing, resources etc.). What is necessary for a good introduction into the new market segments? Which hurdles have to be overcome?
- What do you think is necessary for a market breakthrough of ice slurry applications?

6. Remarks

Do you have any other remarks?

Ice generation	vacuum, direct freeze (triple point), single/two stage systems	scraped surface (drum) (Integral)	ice generation in solution, not at surface, inner side tube evaporator . strong binary solution, internal wiper, (Sunwell), falling film, vertical shell and tube, . static electric potential	direct contact water and circulating, refrigerated fluid, not mixable with water (EA Technology)	super cooled water or water/ ethanol mixture crystallisation initiated after supercooled water exits evaporator (modified shell and tube)	fluidized bed chiller	mixing refrigerant with fresh water/water spray separation, particle mixed with water or weak binary solution	defrost cycle ice generator conventional ice making + additional processing for slurry	capacity, temperature range, media, energy con- sumption, commercially available, etc.
application purpose	 <i>heat source</i> (heat pumps)			 ice slurry			 <i>separation/ concentration</i> (desalination, oil/water separation, juice concentration)		pumpable, temperature, composition, ice concentration, viscosity, enthalpy, etc.
global application		storage	transport		refrigeration/freezing		ice (harvesting) (flake, crushed)		way of application
					direct contact	indirect contact, secondary refrigerant	direct contact		
user		variable loads (peak shaving), discontinuous operation, time dependent energy prices, max. installed capacity, etc.	district cooling, refrigeration installation at distance (R717, R290, ..), flexible use, etc.	fish, agriculture pro- ducts, concrete, displays, etc.	air-conditioning, supermarket cooling/free- zing, dairy industry, food industry, process cooling etc.	fish, concrete, meat, display etc.			specific application requirements: composition, temperature, toxicity, capacity, new/existing installations, legal requirements, etc.

Appendix B Results of the questionnaire

Survey results interviews

- Companies which filled in the questionnaire:
- Fri-Jado B.V.
- Inham-Refrigeration B.V.
- INTEGRAL Energietechnik GmbH
- Solmecs FLO-ICE Systems Ltd.
- STAR REFRIGERATION

Question 1, General

Company	Profile	Main market segments	Function person	Involvement person, ice slurry	Other tasks person (no ice slurry)
A	engineering, contracting, servicing	- industrial refrigeration: cold stores, poultry, chemical industry; - fishing industry: tunnel blast freezers, plate freezers, RSW, FLO-ICE	product manager	- engineering - marketing - sales	no
B	contracting	supermarkets	head refrigeration installation group	engineering services	99% DX installations
C	developer, manufacturer and licensor of Binary Ice Technologies (FLO-ICE, Vacuum Ice), contractor in the field of energy systems (refrigeration, power generation)	- Refrigeration - ORC-Systems	managing director	sales, development, engineering, contracting	80 % in slurry ice
D	--	--	(technical)	--	--
E	--	--	--	--	--

Question 2, Generation of ice slurry

Company	Familiarity generation processes (in scheme)	Awareness other processes	Description processes
A	technical & commercial available: - vacuum ice - scraped surface - defrost cycle - in solution technical: - direct contact water and circulating refrigerant - fluidized bed chiller	- ice production on a vibrating plate (wall)	<i>vacuum ice:</i> principle: triple point conditions, compression and condensation water vapour or desublimation water vapour; composition: very small crystals, about 20% ice/80% water after crystallisation process; status: pilot plant with normal refrigeration is being built at company, plants with steam already commercially available ice cap.: interesting above 1 MW; primary medium: NH₃; temp.: $\geq -0,5$ °C. <i>scraped surface:</i> principle: rotating drum; composition: higher concentration additive in solution and (at) certain ice concentration; status: company sells standard units 2,5/5,0/7,5 tons (per 24 hours) installation: direct contact, no storage tank, seawater as medium ($\approx -2/-2,5$ °C; indirect system with storage tank; cap.: 2,5-5,0-7,5 ton (24 hours); costs: $\pm$ Dfl 3500,-/kW; media: primary R507, secondary TALIN (ethanol) or seawater; temp.: TALIN -4 $\rightarrow$ -6 °C, seawater -1,9 $\rightarrow$ -2,3 °C. <i>Defrost cycle:</i> composition: hard ice crystals in solution (bad for direct contact); status: commercially available (used in fishing industry, but with above described disadvantages); cap.: max. 50 ton/24h (hard ice); media: CFC/HCFC; temp.: ice slurry $\geq -2,5$ °C (first subcooled ice).
B	- scraped surface	yes	<i>scraped surface</i> principle familiar; composition familiar; technical installation familiar.

Company	Familiarity generation processes (in scheme)	Awareness other processes	Description processes
C	- vacuum direct-freeze - scraped surface - vertical falling film	none	<i>Triple point vacuum ice generation:</i> Ice/water mixture with small amount of additives such as NaCl and other minerals. Commercially available. Installations of approx 9MW (ice machine). Production capacity: 350 t/d and 600 t/d per unit. Cost per kW installed: approx. 750 DM/kWRef. 'Water as refrigerant'. Temperature range of slurry: -0,5 / -4 °C. Scraped surface heat exchangers (FLO-ICE): Ice/water mixture with small amount of additives such as ethanol, NaCl, CMA etc. Commercially available. Installations of approx. 2,5 MW. Production capacity: 0,5 t/d - 50 t/d per unit. Cost per kW installed approx. between 1000 and 2000 DM/kWRef. Refrigerants preferably natural substances s.a. propane, ammonia etc. Temperature range of slurry: -1 / -40 °C.
D	--	--	--
E	- drum, scraped surface, direct experience - vacuum system - Sunwell system - EA technology direct injection system - Paradis superchiller	- development of larger drum by Star in association with Integral, larger system more suitable for sea-water applications and has a higher capacity	<i>scraped surface</i> The plant (larger drum) is commercially available with complete systems, available with R22 or ammonia. The first plant was installed in a fish factory in Scotland in January 1996. Other projects include a trawler and a chemical plant (pigment manufacture). Approximate cost £ 1000/kWR for 1 to 10 TR system. Major benefit is the use of 1% NaCl solution. Minimum temp. ≈ -30 °C with ethanol.

Question 3, Purpose for generating ice slurry

Company	Purpose for generating ice slurry
A	company doesn't have experience with other application purposes, but these can be very interesting, possible applications: schools, douches: hot water; airco : cold.
B	--
C	- Heat source for heat pumps: No special technology, only that the heat demand governs the kind and size of the storage tank and not the cooling load. - Separation and concentration: Freeze concentration of juice etc. is known and widely used technology (also beer, wine, black liquor, pulp..) Separation/concentration of oil/water mixtures is new and patented.
D	--
E	no practical experience of these applications

Question 4, Global application of ice slurry

Company	Global application ice slurry
A	storage/transport/consumption
B	--
C	Do not agree with this division. a) Slurry ice is either used as secondary refrigerant (energy density), i.e. as transport medium and/or used as storage medium. b) Consumption means 'harvesting' ice from the ice maker for e.g. immersion cooling of products. a) and b) have different background. Whereas a) is competing with chilled water, brine or evaporating refrigerant, b) is competing mainly with ice makers and to some extent with chilled water. Under a) the enthalpy prevails and under b) the heat transfer is the important issue.
D	--
E	- consumption , indirect must be subdivided depending on whether high heat transfer or reduced pump volume is desired, eg. high heat transfer for better use of 'evaporator' surface vs reduced pump volume for efficiency.

Question 5, Users of ice slurry (A)

Company	Description user applications of ice slurry
A	fishing industry: - production ice out of fresh water or sea water to chill fish, - capacity between 5 tons/24h → 100 tons/24h, - temp. ice $\geq -2,3$ °C (no freezing fish).
B	- indirect system with cold storage for a number of cold rooms.
C	Air cooling: Air conditioning and space cooling Air dehumidification systems Retrofit of plants with lack of cooling capacity, transport- and heat transfer performance Thermal storage systems (ice storage) Commercial refrigeration: Supermarkets Cold stores and cold rooms Food industry: Quick cooling of fruits and vegetables after harvest Immersion cooling of fish after catch and/or slaughter Immersion cooling of packed food (e.g. bags after autoclave) Meat industry (boning rooms, poultry cooling, hides, etc.) Dairy industry (e.g. after pasteurisation, UHT-treatment), ice storage Breweries, beverage industry (also: concentration), ice storage Industrial applications: Fish cooling (on board, on land, transport) Cooling of tools, plastic industry Chemical processes requiring high cooling rates or removal of exothermic heat Compressed air drying Environmental applications: Replacement of directly evaporating refrigerant Desalination Separation of oil/water mixtures
D	Thermal Storage where widely ranging loads are encountered. Max. advantage is taken of the use of 'Off Peak' power tariff. Air Conditioning, Food Processing and initial cooling of fruit and vegetables, where high initial loads occur followed by low holding conditions.
E	Most attractive uses are applications where rapid cooling rate is required eg trawler, chemical plant, or where ice transport is desirable eg a ring motion in a factory.

Question 5, Users of ice slurry (B)

Company	Experience market segments	Technical requirements users indicated market segments	Technical and commercial requirements sufficient?
A	- supermarkets, - fishing industry, - process industry.	<i>supermarkets:</i> - indirect, - cap. approx. 50 kW, - temp. - 5 °C, - peak shaving, - all retrofit; <i>fishing:</i> - direct contact, - 2,5-5,0-7,5 tons/24h → freeze trawlers, - ≥ 100 tons/24h → fresh fish, - temp. range -1,9 → 2,5 °C, - all new.	- no, because of the fact that the capacity is too small, - the technology has to be proved into practice, which is not the case in most market segments.
B	- pilot plant at the company, - one plant in Belgium with a number of cold rooms.	- about toxicity, - new, - temperature range -4 / -5 °C	--
C	With almost any application	Answer already given in the 'applications' since the requirements are self-explanatory	Question not understand
D	- thermal storage for air-conditioning, - hydro cooling for vegetables, - chilled cabinets in supermarkets, - controlled temperature in laboratories - fish freezing in trawlers, - soft drink concentrates.	- safety, low toxicity, not harmful to foodstuffs, - environmentally friendly, - reliable and easy to maintain, - performance (C.O.P.) at least comparable to primary refrigerant systems, - major pipework easy to install, with non specialised labour, - primary refrigerant must be kept to a minimum.	The technical and commercial requirements of ice slurries are acceptable for the applications in which they are used. In due course ice slurries will be used for lower temperatures down to -40 °C and the technical requirements will need to be satisfied with on-site tests.
E	- fish - chemical - building services	Each job is different,. The benefit of FLO-ICE is that it offers a set of new solutions to old problems eg melt-rate in traditional thermal store ice banks.	Even larger units would be beneficial.

Question 5, Users of ice slurry (C)

Company	Legal requirements	Stimulating measures for introduction	Suitable generation process(es) for distinguished applications
A	- use of refrigerant, - tariff of kWh for energy consumption, - installed electric capacity	- environmentally harmless, - quality improvement (fishing), - energy savings.	- vacuum ice, - scraped heat exchanger
B	--	--	- scraped heat exchanger, - super cooled water or water/ethanol mixture
C	- pressure vessel codes - safety requirements - environmental regulations - regulations for food (e.g. immersion cooling)	not known	FLO-ICE for capacities below 500 kW and temperatures from -1 °C to -40 °C. Vacuum Ice for capacities from approx. 200 kW to 3000 kW and temperatures of approx. 0 °C.
D	The strength of pressure vessels and appropriate material tests will be carried out in accordance with the legal requirements i.e. BS 5570?, Lloyds, TÜV, Norsk Veritas etc. Performance testing is an option specified by customer.	Teach-ins and reading of technical papers are an ongoing requirement. Most important is to have more ice plants with a wide variety of applications which give market confidence. The reason for increasing the number of ice slurry units in the market place is that there are market advantages i.e. less primary refrigerant, higher energy savings, new applications, etc.	Vacuum ice for large capacities - above 300 kW at 0 °C with water having a small amount of impurities. Slurry ice using salt, sugar or alcohol solutions for capacities up to 100 kW with temperature down to -40 °C.
E	- pressure vessel design - machinery directive	new requirements for rapid chilling	Direct contact is only possible with NaCl ice, minimum salt content is only possible with vacuum is or the Star/Integral drum.

Question 5, Users of ice slurry (D)

Company	Practice experience	Other promising market segments	Requirements for market breakthrough
A	<i>benefits:</i> faster chilling time of product → better quality; <i>problems:</i> heat exchange of a HFC is worse than of R22, the overall C.O.P. decreases.	<i>applications:</i> - direct cooling of vegetables, - air-conditioning; <i>reasons:</i> - too small capacity, - also the additive in the solution.	- lower price of scraped heat-exchangers. - more support from government and institutes.
B	keep medium (water/alcohol mixture) in a good shape.	--	heat exchangers in a capacity range of 25 - 50 kW
C	<i>benefits:</i> small pipes, low pumping power, low installed capacity, small storage, high heat transfer, high energy density, no (little) emissions, transport properties <i>problems (solved):</i> freezing-up of evaporators, control of ice concentration <i>pay-back:</i> 'no rule of thumb', in air conditioning typically 2 -5 years	All mentioned in previous list. Introduction done gradually. Hurdle is general acceptance of a new technology (as always) and education/training of users and installers.	Sales, sales, sales! However, first users have to be educated and trained. Another hurdle are the multinational and/or large companies who find it difficult to accept technology from a small company.
D	Improved design of mechanical parts ice scraper mechanism. Moving? the use of very low salt concentrations with greater reliability. Payback period for design changes minimal as changes simplify design + reduce manufacturing costs.	Low temperature applications down to -40 °C for cold stores merchant ships, supermarkets etc. in compact sizes up to 250 kW. Design work is continuing in this area but experience of actual installations is required. Greater market penetration to give more reference plants.	The use of ice slurries by major suppliers of refrigeration equipment.
E	. Reducing bottlenecks in processes . Improving product quality	- Preservation of animal skins - Replacing CFC's in existing equipment	User experience

Question 6, Remarks

Company	Remarks
A	--
B	--
C	--
D	The use of ice slurries in areas using conventional refrigeration has great potential. Users are gradually becoming aware of this new technology, but they need to see more plants operating where the advantages will be more apparent.
E	We have only scratched the surface of the possible applications - we think of a new one every week!

Appendix C Licensees of FLO-ICE

Survey licensees FLO-ICE

Country		Licensee	Sub-licensee
GER	Germany	Erba FLO-ICE Tec Binäreis GmbH	Erba Kälte GmbH UNELCO AG ELCO Matériel Electrique
A	Austria		
CH	Switzerland		
L	Luxemburg		
N	Norway	FLO-ICE-TEK Binaeris AS	Air et Chaleur
UK	United Kingdom	STAR refrigeration	
NL	The Netherlands	INHAM Refrigeration B.V.	
B	Belgium		
IS	Iceland		
F	France	Bizem SARL	

Integral Energie Technik GmbH takes care of Denmark, Italy, Spain and Czech Republic.

Solmecs FLO-ICE Systems Ltd. takes care of each other country.

Between INHAM Refrigeration B.V. and Fri-Jado B.V. a co-ordination agreement has been concluded based on exclusivity. The agreement concerns the technology of FLO-ICE and the supply of scraped heat exchangers in the field of commercial refrigeration.