Case for support – An experimental and theoretical study of slurry ice formation and release in a periodically supercooled falling liquid film.

Part 1:Previous research and track record
1.1 Relevant background

- Pumpable slurry ice has emerged as a promising heat transfer fluid and thermal storage medium but the limitations of current slurry ice manufacturing technology are inhibiting widespread adoption.
- Most ice slurry generators are of the closed loop type in which an initial charge of water plus freezing point depressant in a storage tank is progressively transformed into a homogeneous ice slurry suspension by continuous recirculation past a refrigerated surface. Ice formed on or near the surface is removed by motorised scraping.
- The majority of publications on the manufacture and use of ice slurries have appeared in the last ten years, and the most significant ones in the last three years e.g. [1,2,3].The state-of-the-art will be embodied in a forthcoming Handbook on Ice Slurries, to be published jointly by the International Institute of Refrigeration, (IIR), and the American Society of Heating Refrigeration and Air-conditioning Engineers, (ASHRAE), late in 2003.
- The European centre of excellence is based in the Danish Technological Institute in Aarhus, which was set up in 1993. The Oak Ridge National Laboratory is the focus of US ice slurry research. In the UK the heat transfer properties of ice slurry are being studied at Brunel University, and the use of ice slurry for cleaning heat exchangers is being examined at the University of Bristol.
- The involvement of the applicant in this research area dates from 2000 and arose whilst developing a design for a high efficiency two-stage refrigeration system suitable for use by supermarkets, [4]. This design calls for pumpable ice to be manufactured overnight at off-peak tariffs and used to condense refrigerant in a direct expansion cooling system, [5,6]. Chief refrigeration engineers of all the main UK supermarket groups, and some European and US chains were approached by the applicant with the aim of installing and testing a demonstration plant. All expressed interest in the concept but all expressed reservations about the cost and reliability of current slurry ice generators. Both of these factors arise from the need for mechanical removal of ice from a refrigerated surface.
- The applicant started work in 2001 on the design, construction and testing of a novel ice generator which would be reliable, cheap to make and cheap to run.
- During the past two years, based on the concepts described in [7], a small unit has been built and shown to work well, [8,9,10].
- This new ice generator does not employ mechanical ice removal and so creates new opportunities to improve the technology of slurry ice manufacture which will make ice slurry more acceptable to end users.
- One such novel and timely opportunity is to combine the new ice generator concept with existing falling film process technology and this is the subject of the present proposal and a patent application, [11].
- A very recent publication describes a CFD model of ice formation in a laminar falling film, [12].
- There have been no published reports of any previous experimental studies of the use of falling film technology for the manufacture of ice slurry.

1.2 Other related research by the applicant.

- The applicant has recently reviewed new and potential uses of slurry ice as a heat transfer fluid, [13]. During the past two years he has also worked on the use of ice slurries for fire fighting, [14,15,16,17]. He has also continued the development of the concept of a high efficiency refrigeration system for large scale applications, [18,19], and is currently engaged in a CFD study of the cooling of hot gases and hot surfaces using atomised ice slurry.

1.3 General track record

- Prior to his involvement in ice slurry research, the applicant has a research record covering a wide range of experimental and theoretical studies of industrially important heat and mass transfer processes, with more than 150 publications (journal articles, conference proceedings, book, book articles).

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Part 2: Description of the proposed research and its context

2.1 Industrial context of proposed research

Slurry ice is made by supercooling an aqueous solution (water plus freezing point depressant, referred to as a binary fluid) by contact with a refrigerated surface. In practice this is usually achieved by pumping the binary fluid through a refrigerated pipe and simultaneously removing ice formed at the pipe walls using a motorised scraper. These devices are expensive to build and operate and are unreliable and one of the stated main goals of the international ice slurry community is to develop an ice generator without surface scrapers. The proposed research study will help realise this goal.

The applicant has recently demonstrated the practicality of an innovative engineering solution to the problem of ice removal, which obviates the need for mechanical scrapers and opens the way for the use of new ice generation systems such as the falling film system proposed here. The industrial relevance of the proposed research study is evidenced by the attached letters of support

2.2 Academic context of the proposed research, novelty and timeliness

The aim of the proposed research study is to elucidate the physics of time-dependent ice formation and release in a highly disrupted falling film of dilute ice slurry as a function of operating variables such as wall temperature, film flow rate and inlet slurry composition using a combination of experimental and computer modelling techniques.

It is evident from the steep rise in the number and nature of publications on slurry ice technology in the very recent past that this is a timely research topic of international importance. The novelty of the proposal is such that patent protection is being sought, [11].

2.3 Description of the proposed novel ice making system

2.3.1 Introduction

Pumpable ice slurry consists of a suspension of fine ice crystals (nominally in the size range 0.1 to 0.01 mm equivalent spherical diameter) at concentrations up to about 35% by mass in a fluid consisting of water plus a freezing point depressant. Ethanol is commonly employed as a freezing point depressant and this will be the additive used in the proposed study. The nature and properties of ice slurries depend, *inter alia*, on composition and concentration of binary fluid feedstock or mother liquor, and method and conditions of production, [1,2,3].

Supercooling of the binary fluid leads to precipitation of ice crystals on and near the refrigerated surface. In existing devices the bulk of this ice is removed by scrapers and transferred to a gently stirred storage tank from which dilute suspension is recirculated to the refrigerator until the required suspension concentration in the tank is achieved. The presence of a layer of ice on the chiller surface has a detrimental effect on the overall heat transfer coefficient of the chiller. As ice precipitates in a closed loop system, the concentration of freezing point depressant in the remaining binary fluid rises and this acts to “lubricate” the suspension preventing agglomeration of the tiny ice crystals. This also means that the freezing point of the remaining fluid returning to the refrigerated pipe is correspondingly lowered as the ice concentration in the storage tank builds up, a phenomenon known as temperature glide.

If a known volume of binary fluid of known initial composition is partially converted to a homogeneous ice slurry suspension then the concentration of ice in suspension (assumed to be created from pure water) and the new freezing point of the remaining (concentrated) mother liquor can be calculated from the new composition of this liquor. For a given initial binary fluid composition the temperature of the chilled surface can set a limit to the ultimate concentration of ice in a suspension. It is thus possible to generate ice slurry of any required concentration by judicious choice of initial mother liquor composition and operating temperature of the evaporator.

In existing scraped surface devices and starting with a given mother liquor composition, it is imperative to maintain the chiller surface temperature within close tolerances to prevent complete freeze-up and damage to scraper drives. Freeze-up and damage frequently happens but is not a problem with the novel system to be used in the proposed study.

This novel system comprises a recuperative refrigeration circuit which allows slurry ice to be produced in a falling film without the need for continuous surface scraping. The refrigeration circuit is designed to thermally de-ice the vertical chiller plate surfaces in a periodic fashion with minimum parasitic energy consumption. Consequently the ice production process occurs in a series of transient liquid supercooling episodes. The study of the dynamics of transient heat and mass transfer processes in a supercooled falling film of binary fluid on a vertical chilled plate is therefore the focus of the proposed study.

Finding optimal conditions for the operation of the system as a whole will depend on how a dilute ice slurry responds to the conditions created by the proposed design i.e. how much additional ice is precipitated from solution and how quickly and where in the film, how much of the precipitate is washed off the plate as slurry and what is the nature of any adhering ice film and its rate of formation and growth? How do these processes depend on the frequency and amplitude of temperature cycling of the plate?

2.3.2 The recuperative ice generator

The evaporator head

Almost all commercial slurry ice generators are essentially direct expansion refrigerators with an evaporator section designed to supercool a binary fluid, with ice build up on the chilled surfaces being critically limited by mechanical removal, such as scraping.

The novel feature of the new system is that de-icing is achieved thermally by using two identical heat exchangers through which the direction of refrigerant flow can be reversed at optimal frequency. The evaporator head therefore has twice the heat transfer surface of a scraped surface device of similar capacity but has the great advantage of operating without any motorised moving parts and with almost free defrost.

The pair of heat exchangers (4a and 4b in Fig.1 and Fig. 2) form the interface between the refrigeration circuit and the ice making circuit, as shown schematically in Fig. 2.

In a small prototype system recently built and tested by the applicant the heat exchangers were simple vertical copper tubes, with refrigerant on the inside, immersed in the flow of binary fluid, [9], but in the design now proposed they will be commercially available corrugated stainless steel plates (sold as Turbochillers, see photographic element of Figure 2), with refrigerant on the inside, and wetted on the outside by a falling film of binary fluid or dilute ice slurry. The plates are 1.5m wide and 1m high with a cooling capacity of around 10kW.

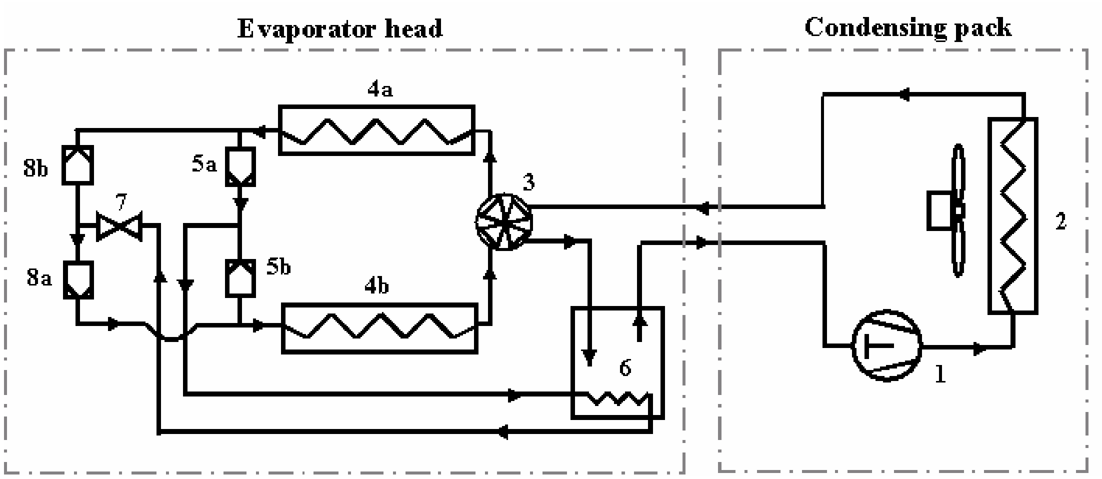

Figure 1. Refrigeration circuit for recuperative ice generator

1. Compressor, 2. Air-cooled condenser, 3. Reversing valve, 4a,b. Turbochiller plates, 5a,b. Check valves, 6. Efficiency booster, 7. Expansion valve, 8a,b. Check valves.

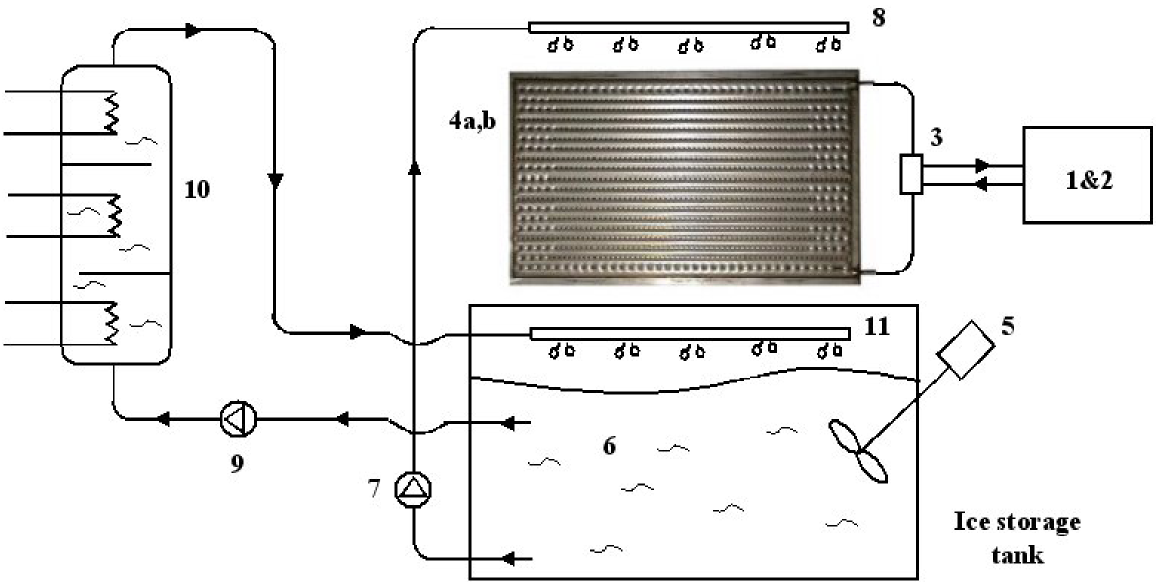

Figure 2. Arrangement of three integrated flow circuits.

1&2. Compressor plus condenser. 3. Valving arrangement for flow direction control. 4a,b. Pair of heat exchanger plates (evaporator and sub-cooler) located above slurry tank. 5. Low speed stirrer. 6. Ice slurry. 7. Slurry pump. 8. Ice slurry distributor. 9. Slurry pump. 10. Ice discharge heat exchanger. 11. Spent slurry spray distributor.

Mode of operation of the refrigeration circuit
Referring to Fig 1, the flow of refrigerant from the condenser pack [compressor (1) and air-cooled condenser (2)] is fed to a reversible four-way valve (3), which is used to direct the refrigerant stream to either one of the pair of exchangers (4a or 4b). Fig 1 shows the flow being directed by the four-way valve (3) through heat exchanger (4a), which will have previously been in ice-making mode and so partially coated with ice. Initially hot compressor exhaust gas will pass through the air-cooled condenser (2) and actually condense in (4a), so rapidly releasing the adherent ice. As the temperature in unit (4a) rises towards the ambient air temperature, condensation begins to occur in the condenser (2) with warm liquid from (2) now passing to (4a), whose temperature will therefore not rise above the condensing temperature set by the fan speed controller on (2).
Subcooled liquid refrigerant leaving the heat exchanger (4a) is then directed by check valves (5a,b) [which are operated by the differential pressure between the suction and delivery lines] to an efficiency booster (6) (a liquid accumulator fitted with a heat exchange coil), and then to an expansion valve (7). The resulting wet vapour is then directed via check valves (8a,b) to the second heat exchanger (4b), which, acting as an evaporator, now enters the ice-build mode. Spent vapour from (4b) then exits to the four-way valve (3) and is directed to the efficiency booster (7) and thence to the compressor suction port, (1). Since the temperature change of the refrigerant in passing from exchanger (4a) to the exchanger (4b) is small when both plates are continuously wetted by the falling film of ice slurry, the amount of flash gas formed at the expansion valve is also small and the cooling capacity of the evaporator plate therefore remains reasonably constant. Continuous subcooling of the liquid feed to the expansion valve by recirculated ice slurry is almost energy neutral, since the energy returned to the circulating fluid in the form of heat is almost matched by the improvement in the evaporative effect when feeding the sub-cooled liquid to the expansion valve.

Flow reversal
After an optimal time it will become necessary to de-ice the heat exchanger (4b) because of a falling heat transfer rate caused by build up of surface ice.This is simply achieved by reversing the refrigerant flow direction using solenoid operated valve (3) so that the subcooler becomes the evaporator and vice versa. During this flow reversal any liquid in the exchanger (4a) and associated lines will be sucked back to the unit (6) where it will be evaporated by the subcooling of liquid now entering the coil in (6) from exchanger (4b), again in an almost energy neutral process. Thus compressor work used in the production of this unused liquid refrigerant is recovered via enhanced evaporator efficiency brought about by subcooling. The cyclical operation is therefore referred to as recuperative and results in minimum parasitic energy consumption.

Ice production
The Turbochiller plate has been developed to give ultra-high heat transfer efficiencies when used for chilling water, the corrugated surface creating highly agitated flow in the falling liquid film. Turbochillers have never been used for the production of slurry ice. It is expected that most of the slush ice formed on the surface will be sloughed off under gravity by the agitated flow but that a more persistent layer of ice will build up on the surface, which will need periodic de-icing, as described above. Ice precipitation within the falling slurry film may be expected to vary with position and time during the half-period of the operating cycle.

The first measurable objective of this proposal is to build a proof-of-concept ice generator based on a evaporator head design already shown to work, but in which ice slurry will be created transiently in a falling film of binary fluid.
The hypothesis is that this will prove to be a practical system for producing slurry ice.
The experimental facility has already been carefully designed and will be built by the technician for whom support is requested.

2.4 Work plan

2.4.1 Construction of test facility

The general arrangement of an ice slurry system consists of an ice generator feeding a stirred storage tank from which a homogeneous suspension of ice slurry is pumped to a cooling load and spent slurry is returned to the tank for regeneration. The applicant has recently visited the Danish Ice Slurry Centre in order to benefit from the wealth of experience in building and operating such systems, and the experimental facility shown schematically in Fig.2 has been carefully designed and costed based on advice received. It consists of three interconnected flow circuits. **First**, a direct expansion/vapour compression refrigeration circuit will provide a variable temperature and cooling effect in the evaporator head as shown in Fig.1. Recuperative de-icing will be at variable frequency. **Second**, an ice making circuit will comprise a stirred storage tank from which dilute ice slurry will be pumped at a variable rate to a distributor along the top edges of the evaporator plates. Not shown in Fig.2 is the insulating cover for the plates, which will be integral with the tank. The design and operation of the tank is non-trivial and is based on recommendations in [2]. **Third**, an ice discharge circuit which will allow ice slurry from the storage tank to be pumped to a heat exchanger where the ice can be melted at the same rate as it is created by the evaporator head so that “quasi-steady state” ice slurry production at any desired concentration can be studied.

2.4.2 Experimental methodology
Specific energy consumption (energy used to produce unit mass of slurry at given concentration) will be determined as a function of the variables of the system and used as a measure of overall performance.
These experimental variables and their ranges will be:

- **evaporator plate temperature, controlled by the thermostatic expansion valve setting, in the range 253K to 267K, and measured using thermocouple arrays attached to the plate surfaces**
- **rate of ice slurry feed to the plates, to examine the effect of film Reynolds number in the laminar and turbulent regimes. The critical Reynolds number based on mass flow per unit film width is expected to be around 2000. The slurry flows will be controlled by means of the circulation pumps, and measured electromagnetically.**
- **initial freezing point depressant concentration in storage tank (5% to 20% by mass of ethanol)**
- **equilibrium ice concentration in storage tank (5% to 30% by mass), selected by choosing the ice discharge rate and determined algebraically from the initial and final concentrations of binary fluid, measured by densitometry.**
- **cycle reversal frequency, controlled by means of the solenoid operated 4-way valve (50 s to 600s).**

The second measurable objective is to establish experimentally how the operating conditions of the falling film system influence the dynamics of the production and release of slurry ice. The experimental work will be carried out by the research student.

2.4.3 Theoretical analysis and modelling – methodology
Once the ice concentration in the storage tank has reached the required level, the inlet conditions for modelling the falling film flow will be dilute ice slurry of fixed concentration and temperature. The degree of supercooling and hence ice precipitation in the falling film will be highest near the wall and towards the bottom of the film. Consequently the local freezing point and thermophysical properties of the flow will vary throughout the film. The presence of ice crystals is known to improve the heat transfer properties of a flow and to affect the flow behaviour relative to an equivalent single phase flow. Some ice will adhere to the surface and create a growing insulating barrier to heat transfer, the effect of which will increase with time and affect the heat and mass transfer processes in the film. Periodic surface de-icing returns the system to maximum efficiency. It is to be expected that the dynamics of formation and release of slurry ice will depend on plate temperature, film flow rate and inlet conditions and de-icing frequency. It is hypothesised that for a supply of dilute ice slurry of given composition some optimum combination of these three variables will result in incremental ice slurry production at minimum specific energy.
Modelling of the time and position dependent flow and heat and mass transfer behaviour in a supercooled turbulent falling film with a growing ice film will be undertaken using CFD. The aim will be to consolidate the understanding of the physics of ice production in a periodically supercooled turbulent falling film and to create a basis for the correlation of experimental data and system optimisation.
Predictions will include temporal and spatial distributions of ice concentration and temperature within the film and wall Nusselt number as a function the thermophysical properties of the inlet flow, film Reynolds number and wall Stefan number.
Once a system model has been developed and validated it will be used to explore the effect of film residence time (flow length at fixed flow rate), stage-wise addition of binary fluid to the film (thus manipulating local freezing point and degree of supercooling with vertical position) and other possible system variations.
The applicant has published several papers on the integral analysis of moving boundary problems (Stefan problems) e.g. [21] and has used CFD to analyse a wide variety of commercially important problems, e.g. [22,23].

The third measurable objective is to undertake a system analysis and to construct and validate a computer model which correlates the dynamics and specific energy consumption of ice production in a falling film which is periodically supercooled, and to use the model to explore the effect of selected variations in system design and operation.

2.5 Justifications for funding requests
2.5.1 Refrigeration system
To determine the specific energy consumption the electrical supply to the 3 phase refrigeration unit plus the pumps circulating ice slurry to the plates will be fitted with a power meter and the slurry production rate and ice concentration will be determined as described above.
In order to control evaporator cooling capacity at a fixed evaporator temperature a scroll compressor will need to be fitted with a variable speed drive.
The refrigeration unit needs to be “critically charged” since it does not have the usual liquid receiver (a buffer store) in the circuit and carries the minimum amount of refrigerant needed to operate at full load. This means that the cooling capacity of the condensing pack has to be closely matched to the cooling capacity of each plate

forming the evaporator head and that liquid refrigerant content at certain points in the circuit needs to be monitored until the correct liquid charge is established. This critical charge depends on the volume of the various flow spaces which make up the circuit and one of the challenges will be to minimise the volume of liquid sucked back to the accumulator on each flow reversal. Refrigerant charge and recovery equipment is therefore needed together with strategically placed sight glasses and a liquid refrigerant flow meter. The refrigeration circuit performance will be monitored by using pressure gauges on the delivery and suction ports of the compressor. Suction pressure will be used as an indicator of the evaporator temperature and compressor head pressure will be used as an indicator of condensing temperature, as is the normal procedure with refrigeration systems. The temporal and spatial variations of surface temperature on the Turbochiller plates will be monitored using thermocouple arrays and a data logger. The primary purpose of logging surface temperature data will be for model validation and system analysis and it is not proposed to attempt the experimental determination of local heat transfer coefficients.

2.5.2 Ice making and discharge circuits
Slurry supply to the Turbochiller plates will be by variable speed pumps and flow rate will be measured electromagnetically, [20]. The production rate of ice slurry will be determined from the measured thermal discharge rate needed to maintain selected “steady state” ice concentration conditions in the storage tank. Ice concentration in the tank will be determined from the residual binary fluid composition. Ice particle size distribution, which is dependent on the production process and which influences the flow and heat transfer characteristics of ice slurry, will be determined using a small digital microscope and image analysis software. The discharge heat exchanger will consist of a battery of metered variable power electrical immersion heaters in a well mixed vessel and a slurry pump will be used to transfer ice slurry from the centre of the storage tank to the discharge tank. The storage tank must be slowly stirred to maintain homogeneity of the slurry with spent slurry returning from the discharge unit and fresh slurry entering from the generator.

2.5.3 Modelling work
Modelling will be undertaken using the CFD package FLUENT, and a contribution of 10% of software maintenance costs is requested.

2.6 Relevance to beneficiaries
The outcome of the research will be the knowledge necessary for the design of an ice generator without moving parts and with low specific energy consumption. This will comprise an understanding of the fundamental processes occurring in a falling film ice precipitator together with an understanding of how to manage these processes in a practical device operated in a sequential transient mode using periodic thermal de-icing. Consequent upon this will be a reduction in energy consumption in a number of applications. For example, the dairy industry around the world uses static ice to chill milk on farm during milking time. Solid ice is built up in between milkings (inefficiently) and then used to chill the warm milk (inefficiently). Slurry ice will use far less energy than static ice and will result in better quality milk because of the more rapid cooling. Another important exemplifying potential use of pumpable ice is as a secondary refrigerant to replace current refrigerants in large systems such as supermarkets. The International Energy Agency is currently sponsoring feasibility studies of such systems under a program known as Annex 26 (see www.ornl.gov/annex26). There are numerous other applications of slurry ice which will benefit from the successful outcome of the proposed research, [3,24].

2.7 Dissemination and exploitation
The scientific outcomes will be published in appropriate high profile journals (Intnl Journal of Refrigeration, Intnl Journal of Heat and Mass Transfer) and presented at conferences,(9th UK Heat Transfer Conference and 22nd Intnl Congress of Refrigeration). It is intended to seek funding from the ice slurry community to run an international workshop on ice generation at Exeter towards the end of the project. A web site will be developed which will be a repository for the project outcomes and related science and technology.
The technological outcome will be submitted to the Energy Efficiency Best Practice Programme for inclusion in their list of approved technologies which qualify end users for an Enhanced Capital Allowance when such approved devices or technologies are installed.
Exploitation of the knowledge gained will be through collaboration with a commercial company and funds are requested to cover travel costs to visit prospective partners to discuss future developments.

2.8 Management and resources
Work on this project over the past two years has been very actively pursued by the applicant who will remain fully committed to the successful completion of the research programme. The additional resources needed are a research student and limited technician support. An excellent potential research student has been identified who will be closely supervised and the input of a competent student is essential for the prosecution of the project. The experimental facility has already been carefully designed, the components are readily available and with the help of skilled technician assistance construction can start immediately funds are released. I am requesting 10% of the time of an existing technician spread over the lifetime of the project mainly concentrated

in the first three-month building phase with some time envisaged for subsequent rig modifications. The total cost of the proposed research programme is as low as realistically possible.
The research infrastructure and general resources available in the Department of Engineering at Exeter are adequate and do not present an obstacle to the successful execution of the project. The applicant has relevant experience and expertise in both experimental and theoretical research which will enable him to provide the necessary input and efficient management of the project. He will play a leading role in the modelling study.

2.9 Summary of projected outcomes

- A proof-of-concept 10kW_c slurry ice generator with no moving parts
- Experimental test data over practical ranges of all the operating variables
- Computer based model of the flow and heat and mass transfer processes responsible for ice precipitation from a periodically supercooled turbulent falling film of binary fluid
- Identification of optimum operating conditions and further improvements
- Knowledge to design a full scale prototype for field trials
- Journal publications and patent applications
- Industrial partnership for future research and product development

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