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Applications of Green Secondary Refrigerant (Ice Slurries) in Refrigeration - Some Studies on Ice Slurries

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Abstract—*A scraped surface ice slurry generator has been designed, developed and fabricated with a focus on collection of experimental data related to ice crystallization mechanism in the microscopic scale, heat transfer and fluid mechanics involving agitation and phase change in the macro scale for the ice slurry (green secondary refrigerant) production. Experimental study shows that at different concentrations of antifreezes (PG and MEG), initially the freezing temperature reduces sharply with time (stage 1), then there is sudden rise in temperature for very short duration of time (stage 2) and finally it slowly reduces whereas freezing temperature reduces with increase in antifreeze mass fraction. Freezing temperature is inversely proportional to antifreeze mass fraction.*

Keywords*: ice slurry, depressants, scraped surface generator, performance study.*

1. INTRODUCTION

Ice slurry has a great potential for the future due to wide range of industrial applications varying from comfort cooling and commercial refrigeration to industrial production processes medicine and in the milk production where high peak loads are to be adjusted. Ozone depletion and global warming forced the refrigeration and air-conditioning industry to reexamine the utility of 'old' and industrially viable refrigerants (such as methane, ethane, propane etc) to be attractive, because of their zero ODPs. In the 1930s these have been replaced by new chemical compounds, namely CFCs and HCFCs. The prime advantages of these synthetic materials were nontoxicity and nonflamability, whereas the disadvantage is their impact on environment**.** Besides this the leakage of toxic or/and flammable 'old' refrigerants require leakage free systems or as an alternative a secondary circuit with a special cooling fluid for heat abstraction. It was precisely this development, mainly responsible for the utility of the ice slurry technology in the present scenario.

Recent developments in the ice slurry generator technology and advanced design concepts have made this technology a industrially viable alternative to existing conventional secondary refrigeration systems. Presently, the major research work for development of ice slurry generator has taken place only in developed countries due to very high fixed cost. The scraped surface ice slurry generator is commercially the most technologically developed and widely accepted ice slurry generation process over the last two decades. From the literature review it is clear that the basic understanding of the governing ice slurry crystallization mechanism is rather limited and is still speculative. Further, at present the design of ice slurry generation system are purely in the hands of ice slurry manufacturer who keep detailed operating data proprietary. Therefore there is an urgent need for better understanding of basic crystallization and heat transfer mechanisms to optimize and develop relatively compact, efficient and less costly ice slurry generators.

Ice slurry is a phase-changing secondary fluid consisting of both a liquid state fraction and a solid–state fraction. Depending on the type of additive and additive concentration, the operating temperature for ice slurry can be chosen from 0 to at least -35ºC [1,2]. Beyond the advantages of the traditional indirect systems for lowering the emissions of refrigerants and refrigeration plants, ice slurry is a more efficient secondary fluid than single-phase fluids. Using ice slurry with accumulation increases the possibility to build indirect systems without increasing the energy consumption.

The time required for ice to cover the unscraped cooling surface; the thermal response of the supercooled solution at the onset of phase change; the heat transfer coefficient on the scraped surface with/without phase change, and the growth kinetics of ice film spreading along the cooling surface was studied by Frank et al. [4]. Continuous heat extraction is important for the process of freeze concentration of aqueous solutions, in which water is removed as solid ice. Three typical heat-transfer patterns were identified during the process of freeze concentration in an SSHE. These correspond to the stages of chilling, nucleation, and crystallization, respectively [5]. Heat transfer is an unsteady process in the initial period of ice nucleation or phase transition from aqueous solution. Using the Laplace and inverse transform, and incorporating the initial condition of ice nucleation, an analytical solution of this model is obtained by Frank et al. [6].

Heat transfer phenomena in two types of eutectic crystallizers have been analyzed by Vaessen et al. [7]. Application of the analytical solution leads to the predictions of the growth rate of ice films on different materials, and the temperature distribution in the solid slab right underneath the growing front of the ice film [8]. For ice slurries to become more widely accepted, however, more engineering information is required on fluid flow and heat transfer characteristics. In a practical application, for a given thermal load this would lead to greater than 60% reduction in flow rate and pressure drop compared to chilled water cooling systems [9]. In recent years, a lot of important work has been carried out in order to gather knowledge of the fundamental behaviour of ice slurry in piping systems and heat exchangers [10].

An experimental study was carried out on a scraped surface heat exchanger used for freezing of water–ethanol mixture and aqueous sucrose solution. The influence of various parameters on heat transfer intensity was established [11]. A performance assessment of four main types of ice storage techniques for space cooling purposes, is conducted by David and Dincer [12]. The results show that energy analyses alone do not provide much useful insight into system behavior, since the vast majority of losses in all processes are a result of entropy generation which results from system irreversibility.

A successful way to enhance the thermal capacity of secondary fluid systems is by incorporating microencapsulated phase change material (MPCM) slurry. However, a full understanding of the physical properties and heat transfer characteristics of MPCM slurry in the 2–8 ^{0}C range still is lacking. The experimental data show that MPCM slurry can provide considerable heat capacity in heat transfer applications [13].The characteristics of three different principles of pumps-centrifugal, side-channel and screw were investigated [14]. The heat transfer coefficient and the power consumption of a laboratory scraped-surface heat exchanger (SSHE) were measured when it was used for freezing a 10 wt. % sugar solution. Experimental results show that the heat transfer coefficient with phase change (ice formation) was about three to five times greater than that without phase change [15]. Effect of poly vinyl alcohol (PVA) in inhibiting an increase in ice crystal size in isothermal ice slurries was investigated, and then compared with the effect of an antifreeze protein (AFP), NaCl [16].

A new type of sensor for in-line measurements of antifreeze mass fraction in aqueous solutions is described by Vincet et al. [17]. Latent heat of fusion of ice in aqueous solutions was measured to understand latent heat of fusion of ice slurries. Propylene glycol, ethylene glycol, ethanol, NaCl and NaNO3 solutions were used as aqueous solutions. [18]. The study by Matsumotoa [19] focuses on an emulsion as a new thermal storage material for ice storage. This study by Guilpart et al. [20] compares the performance of several commonly used organic and inorganic ice slurry secondary refrigerants. For ice slurry calculations and modeling, it is important that they are performed with accurate thermo physical property values of the aqueous solution and of ice. For ice slurry applications there is a need for accurate freezing point data and for more basic thermo physical property data at low concentrations [21].

In the present experimental study ‘scraped surface ice slurry generator’ of 5 litre capacity has been designed, developed and fabricated with a focus on collection of experimental data related to ice crystallization mechanism in the microscopic scale, and heat transfer and fluid mechanics involving agitation and phase change in the macro scale for the ice slurry production [15]. The main components of ice slurry circuit are: Scraped surface ice slurry generator with a scraper, condensing unit, pump and a storage tank. The scraped surface ice slurry generator consists of a circular shell and coil type heat exchanger cooled by an evaporating refrigerant flowing in a spiral shape coil around the outer shell side. The inner cooled surface of the shell is scraped by spring loaded rotating blades to prevent crystal depositions. This scraping action is required to prevent the formation of an ice layer on the ice generator walls. Turbulence is mechanically induced into the ice slurry flow by the action of the rotating scraper blades mounted in the centre of the generator, thus greatly enhances the heat transfer rates and thus facilitating the production of a homogeneous ice slurry mixture. This unit supplies the refrigerant to the coil of the ice slurry generator (referred as evaporator in the refrigeration cycle) where evaporating refrigerant at lower pressure withdraws heat from the binary solution which is finally converted into ice slurry. Experimental studies have been performed using water and various depressants such as propylene glycol, methyl alcohol, ethyl alcohol in different proportions. Performance studies have been conducted for wide range of operating variables.

2. RESULTS AND DISCUSSIONS

In continuation to our previous work [22] **‘**Development of Scraped Surface Ice Slurry Generator’ experiments were carried out. The aqueous solution of antifreezes, Propylene Glycol (PG) and Mono Ethylene Glycol (MEG) with water at different weight percentages 10%, 20% and 30% of antifreezes and 90%, 80% and 70% of water respectively were subjected to the freezing process. The coolant temperatures were measured with RTD. Recorded temperatures of aqueous solution of Antifreezes (PG and MEG) at various concentrations are plotted (Figs.1,2,3,4,5 and 6) with respect to freezing time of ice slurry for PG and MEG, respectively. With antifreeze PG, the lowest ice slurry temperatures achieved are -2.9 ^{0}C, -6.4 ^{0}C and -11.0 ^{0}C at 10%, 20% and 30% concentrations respectively, whereas with antifreeze MEG, lowest ice slurry temperatures achieved are -3.4 ^{0}C, -7.1 ^{0}C and -11.9 ^{0}C at 10%, 20% and 30% concentrations respectively. Freezing temperatures vs. antifreeze mass fraction is shown in Fig. 7. A photograph of ice slurry formation is shown in Fig. 8.

Historical time curves (recorded temperatures of aqueous solution of antifreezes, refrigerant temperatures at evaporator inlet and outlet, refrigerant temperatures at condenser inlet and outlet, ice slurry temperatures at different concentrations), and freezing temperatures vs. antifreeze mass fraction are plotted. Recorded temperatures of aqueous solution of antifreezes, refrigerant temperatures at evaporator inlet and outlet, refrigerant temperatures at condenser inlet and outlet at different concentrations are plotted (Figs. 1 to 3 for PG and Figures 4 to 6 for MEG) with respect to freezing time. From the present experimental ice slurry generation data it can be observed that ice slurry generation process can be divided into three stages- cool down or chilling period, nucleation or unstable ice slurry generation period and stable ice generation period. The first stage (cool down period) starts t_0 to t_1, where t_0 is the starting time of the experiment and t_1 is the time at the end of the chilling period which is the on-set of the super-cooling phenomenon. During the chilling period volumetric ice concentration is zero. As observed in Figs 1 to 3, the freezing temperature reduces with increase in antifreeze mass fraction for PG solution initially chilled continuously without phase change in stage 1. First phase time duration is 1500, 1600 and 2000 seconds respectively for 10%, 20% and 30% concentration of PG. Similar trend was observed for MEG (Figures 4 to 6) but first phase time duration was relatively higher as compared to PG. During this stage the average evaporator temperature decreases sharply which causes increase in the refrigeration capacity and compressor work. Therefore, the condenser inlet temperature increases due to higher heat rejection quantity. Volumetric ice concentration is zero during the chilling period. During this stage the average evaporator temperature decreases sharply due to unsteady state nature of heat transfer through the shell of ice slurry generator. The outlet temperature of evaporator outlet is stabilized when the nucleation period starts.

The second stage (nucleation period) starts from t_1 to t_2, where the ice seeds after the super cooling phenomenon is observed and the volumetric ice concentration increases till its maximum value at the end of this period (at t_2). In stage 2, nucleation of ice particles occurs and it is characterized by 0.5 to 1^0C jump in temperature of the process fluid due to the release of the fusion heat of ice. Finally the third stage (ice slurry generation period) starts from t_2 to the end of the experiment, at t_f. During this stage the ice concentration is maintained constant at its maximum value. During stage 3 the heat transfer is affected by the release of the latent heat of water freezing.

Freezing temperatures vs. antifreeze mass fraction is shown in Fig. 7. Here, freezing temperature is inversely proportional to antifreeze mass fraction. When water freezes out after the temperature of the liquid mixture has passed below the freezing point, the concentration of the additive increases in the liquid-phase. The increased additive concentration implies that the freezing point of the remaining liquid-phase is further lowered and in order to freeze out more ice the temperature of the mixture has to be further lowered below the current freezing point of the liquid. The result is that the fluid has a freezing range rather than a definitive freezing point. Thus by plotting the freezing point as a function of the additive concentration, one obtains a freezing point curve as a function of the additive mass concentration of different freezing point depressants (Fig. 7). Lowering of the temperature of the ice slurry is independent of the effect of the latent heat from the phase change, but dependent on the sensible heat of the mixture. Since it is the advantage of the latent heat in ice slurry that is desired, one desires a liquid mixture where the latent heat dominates. To minimize the influence of the sensible heat, a fluid with a relatively low first derivative of the freezing point curve (flat freezing point curve) is to be preferred.

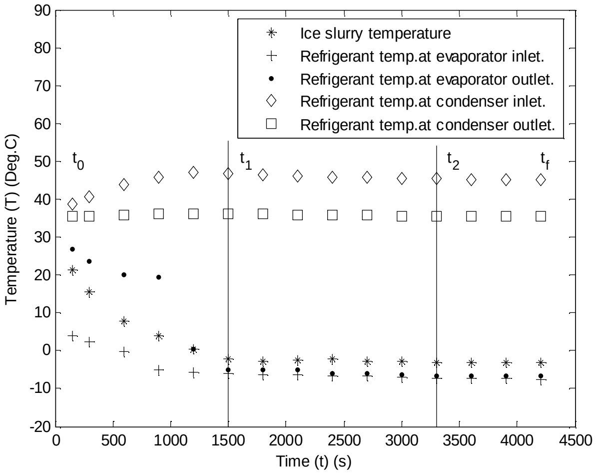

Fig.1. Freezing temperature vs time for PG at 10 % concentration

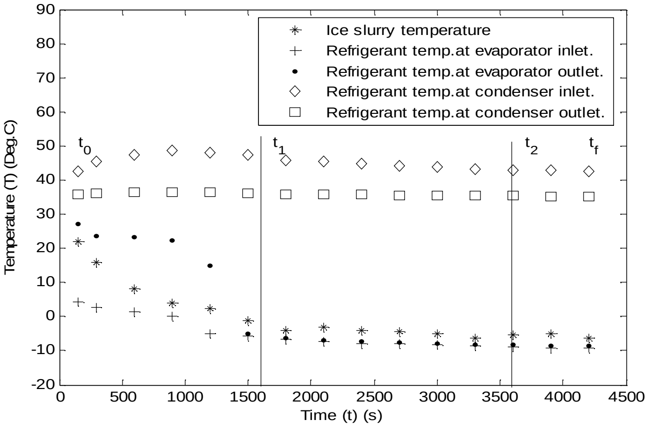

Fig. 2: Freezing temperature vs time for PG at 20 % concentration

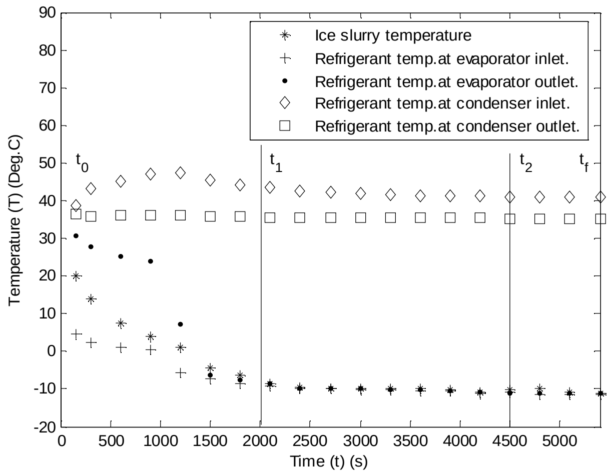

Fig. 3: Freezing temperature vs time for PG at 30 % concentration

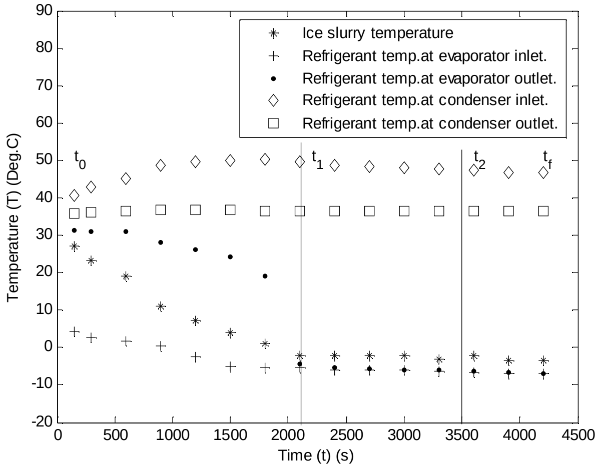

Fig. 4: Freezing temperature vs time for MEG at 10 % concentration

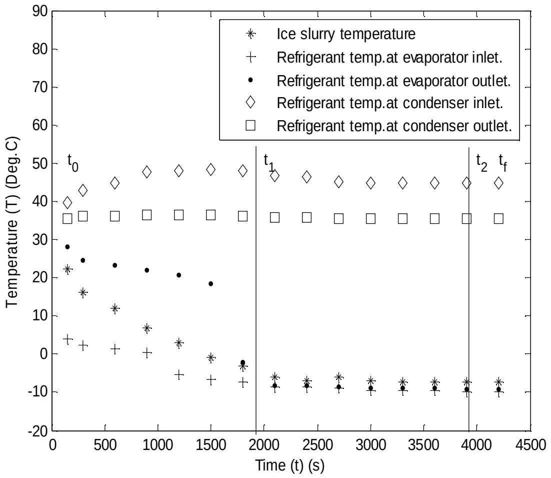

Fig. 5: Freezing temperature vs time for MEG at 20 % concentration

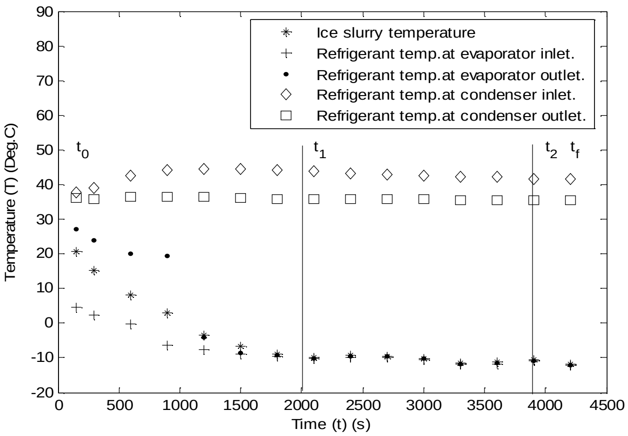

Fig. 6: Freezing temperature vs time for MEG at 30 % concentration

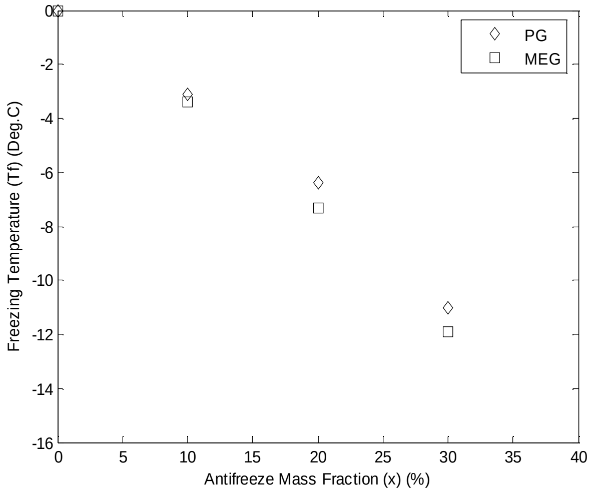

Fig. 7: Freezing curve of water-PG and water- MEG mixture

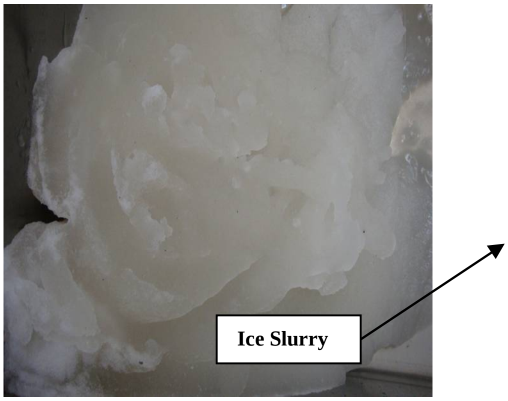

Fig. 8: Photographs of Ice Slurry of -11.9 ^{0}C formation in SSISG using MEG

3. CONCLUSIONS

From the present experimental data it can be concluded that at different concentrations of antifreezes (PG and MEG), initially the freezing temperature reduces with time (stage 1), then there is sudden rise in temperature for very short duration of time (stage 2) then reduces. It is observed that the freezing temperature reduces with increase in antifreeze mass fraction for PG and MEG solution initially chilled continuously without phase change in stage 1. In stage 2 of very short duration, nucleation of ice particles occurs and it is characterized by a distinct jump in temperature of the process fluid due to the release of the fusion heat of ice. During stage 3 the heat transfer is affected by the release of the latent heat of water freezing and freezing temperature is inversely proportional to antifreeze mass fraction [20, 24].

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