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Experimental Studies on a Scraped Surface Ice Slurry Generator

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***Abstract**- In the present experimental study a scraped surface ice slurry generator has been designed, developed and fabricated successfully with a focus on collection of experimental data related to ice slurry production using 10%, 20% and 30% concentrations of antifreezes (PG and MEG). Three distinct stages- chilling, nucleation and stable ice slurry generation period were observed through historical time dependence curves. The minimum ice slurry temperatures achieved are -11.0 ^{0}C and -11.9 ^{0}C respectively for 30 % concentration of PG and MEG. It was further observed that the freezing temperature reduces with increase in antifreeze mass fraction for PG and MEG. Using the experimental data and the present manufacturing technique opens further possibility for development of a higher capacity ice slurry generation machine suitable for industrial application.*

Index Terms- **Ice Slurry, Scraped Surface, Ice Slurry Generator, Antifreezes.**

I. INTRODUCTION

During the last couple of decades, some widely used conventional refrigerants have been identified as harmful for greenhouse substances and also contribute ozone depletion. Therefore, refrigeration industry has been continuously working to develop alternative refrigerants having good physical and thermodynamic characteristics besides less adverse effects on the environment. Simultaneously, the research work has also been done to reduce the amount of refrigerant installations by the use of secondary refrigeration loops. The heat transfer fluid in these loops is generally water or sometimes an aqueous solution which can be replaced by diphasic secondary refrigerants such as ice slurries to improve system efficiencies.

The ice slurry is normally the ice crystals distributed in water or an aqueous solution where different substances are added to achieve reduction in freezing point, viscosity, corrosion behaviour, agglomeration and increase in heat carrying capacity and thermal conductivity of the fluid phase. Ice slurry has a great potential for the future due to wide range of industrial applications, ranging from comfort cooling and commercial refrigeration to industrial production processes and medicine. An important application [1] of an ice slurry system is in the milk production where high peak loads are to be adjusted.

Ice slurry is a phase-changing secondary fluid consisting of both a liquid state and a solid–state fraction (composed of fine ice particles). The main purpose of using ice slurry is to take advantage of the stored cooling energy (in terms of latent heat) in the ice particles (0.1 to 1 mm size) during melting. Sodium chloride, ethanol, ethylene glycol and propylene glycol are the four most commonly used freezing point depressants [2] used by the refrigeration industry. Depending on the type of additive and additive concentration, the operating temperature [3] for ice slurry can be chosen between 0 to -35ºC.

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 exhaustively studied by Qin 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 stages of heat-transfer patterns [5], namely, chilling, nucleation, and crystallization were identified during the process of freeze concentration in a scraped surface heat exchanger. Using the Laplace and inverse transform, and incorporating the initial condition of ice nucleation, an analytical solution was obtained by Qin et al. [6]. Heat transfer phenomena in two types of eutectic crystallizers have been analyzed by Vaessen et al. [7]. Both increasing and decreasing heat transfer rates have been observed in crystallizing conditions at increasing scraping rates. Differences are attributed to geometrical crystallizer characteristics and solid content [8].

For ice slurries to become more widely accepted, however, more engineering information is required on fluid flow and heat transfer characteristics. An experimental study [9] 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. 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 [10] show that the heat transfer coefficient with phase change (ice formation) was about three to five times greater than that without phase change. Effect of poly vinyl alcohol

(PVA) in inhibiting an increase in ice crystal size in isothermal ice slurries was investigated by Inada and Modak [11]. Using PVA, which exhibits thermal hysteresis, is a novel technique to completely inhibit the increase in ice crystal size in isothermal ice slurries. A new type of sensor for in-line measurements of antifreeze mass fraction in aqueous solutions is described by Ayel et al. [12]. Its principles of operation are based on the exploitation of the temperature rise that accompanies the freezing of an undercooled solution. Latent heat of fusion of ice in aqueous solutions was investigated by Kumano et al. [13] in order to understand the characteristics of ice slurries used in ice thermal energy storage systems.

The study by Matsumotoa et al [14] focuses on an emulsion as a new thermal storage material for ice storage. The results indicated that one emulsion was a W/O type emulsion, while the other was an O/W type. Finally, adaptability of the two emulsions to ice storage was discussed, it was concluded that a high performance ice slurry could be formed by the W/O type emulsion. Study by Guilpart et al. [15] compares the performance of several commonly used organic and inorganic ice slurry secondary refrigerants. This study was based on thermo physical assessments carried out at different operating temperatures. For ice slurry applications there is a need for accurate freezing point data and for more basic thermo physical property data at low concentrations [16]. An analytical model has been developed by Hawlader et al. [17] to predict the growth of ice around the injected super cooled coolant droplets, which involves phase change and heat transfer between layers. Theoretical and experimental work on a novel ice slurry producing system utilizing inner waste heat was proposed by Li et al [18]. This system consists of two major processes: an evaporative super cooling process and a liquid dehumidification process. Lu and Tassou [19] investigated several types of phase change materials for the preparation of PCM slurries which have potential for cooling applications.

Heat transfer from a jacketed wall of a scraped-surface heat exchanger (SSHE) numerically simulated by Baccar and Abid. [20] to analyse the hydrodynamic and thermal behaviour under various operating and geometrical conditions using three-dimensional form of the Navier-Stokes and energy equations. Results show that geometrical and operating parameters can strongly affect the performance of a heat exchanger. An increase in the number of scrapers contributes to a higher frequency of the scraped film which would improve heat transfer performance. With more than four blades, radial dispersion decreases and a rigid-body rotation takes place. The growth pattern related to the potential for crystal growth as well as the crystal surface topography have been studied by Grandum et al [21].The crystal shape and size were found to be strongly dependent on the super cooling in the crystal's surrounding liquid in between a transition temperature. An experimental investigation of a scraped surface heat exchanger (SSHE) was undertaken by Dumont et al. [22] using visual observations and the electrochemical technique in order to study the transition between laminar and vortex flows and to evaluate the wall shear rates. It was established that flow patterns in a SSHE are noticeably different from those observed in an annular space in the same conditions. A bubbling device was applied by Zhang et al. [23] to an experimental dynamic ice making system to suppress ice adhesion to the cooling wall. The experimental dynamic ice making system employed an air compressor to create air bubbles, and for the sake of this purpose, its ice slurry generator was set up vertically. It was concluded that the air bubbles are effective to suppress ice adhesion to the cooling wall; however, the air blowing rate of the air compressor should be optimized. Lasvignottes et al. [24] demonstrated the feasibility to produce ice slurry from super cooled water. This technology which does not use extra mechanical energy source to operate is a promising alternative to the actual technologies. However the design must be very accurate to control the super cooled degree at the outside of the evaporator.

A functional fluid was made by adding a small amount of additive to a water silicone-oil mixture with 90 vol % water content, and the functional fluid was transformed into an ice slurry by cooling while stirring. The new ice formation system, proposed by Matsumotoa et al [25] for ice storage based on the results of previous studies, demonstrated that the ice slurry could be formed continuously for 10 h. Experiments were carried out, varying operating conditions, and an optimal operating condition was determined to improve performance of the present system.

A physical model to investigate the non-isothermal freezing kinetic in ice slurry systems was built by Kousksou et al [26]. Matsumoto et al [27] had proposed application of ice slurry to a cold storage of foods for widely using the ice slurry. A new ice slurry utilizing the food additive trehalose was tested using the “harvest method”.

Heat transfer in presence of a high viscosity fluid may be substantially enhanced using heat exchangers supported by a mechanical agitation system that can also “scrape” the exchange surface. In this case, heat transfer efficiency depends strongly on exchanger and agitator geometries, agitation methods as well as fluid characteristics and heat transfer conditions [28].The study performed by Yataghene et al [29] is focused on experimental analysis of the flow patterns inside SSHE under isothermal and continuous flow conditions. Experimental flow pattern analyses are the basis for further experimental explorations of mixing and heat exchange mechanism. Thongwik et al [30] studied the heat transfer phenomenon of melting slurry ice on external surface of a copper helical coil. The experimental results show that, with small coil diameter, high mass flow rate of circulating water and low ice fraction, high heat transfer coefficient of the slurry ice at the warm helical coil surface is obtained.

Most crystallization models for ice slurries are based on the equilibrium thermodynamic approach. Che´gnimonhan et al [31] presented results of simulations grounded on classical nucleation theory and crystal growth included in global Nakamuratype kinetics coupled with the one-dimensional nonlinear heat equation, another way to model the phase change.

Ice storage is a potential energy saving method for air conditioning systems and is an ideal material for ice storage. The conventional ice slurry producing method using super cooled water suffers from the instability of ice block and depends heavily on electric power. A novel ice slurry producing system utilizing inner waste heat was proposed by Li et al. [32]. Compared with the conventional system, this new system can alleviate the burden on electric power and raise the efficiency. The basic crystallization principles and heat transfer mechanisms in current ice generators are not yet fully understood. To elucidate the heat transfer mechanisms, heat transfer measurements are presented by Stamatiou et al [33] in a prototype compact ice generator. Turbulent fluid flow and related solid particle behavior in the direct vicinity of the heat exchanging surface of a scraped heat exchanger crystallizer was studied by Pascuala et al [34]. The main goal was the design of scraper geometries that enhance heat transfer by perturbing the thermal boundary layer, and effectively scrape off particles that nucleate, grow and adhere onto the heat exchanger surface. The Ultrasonic Doppler Method (UDM) has been applied by Vuarnoz et al. [35] to the process of ice slurry generation by direct injection of a refrigerant into an aqueous solution. The main objective of this work has been to investigate the fluid dynamic behavior of evaporating refrigerant drops in an immiscible fluid and the approach taken has been to evaluate how suitable the UDM technique is for such investigations.

Pronk et al [36] performed a dynamic simulation of an experimental set-up in order to predict heat transfer coefficients in a fluidized bed ice slurry generator. A comparison between experiments and results from simulations pointed out that both models overestimate heat transfer coefficients and that crystallization does not affect the heat transfer process significantly. A possible explanation for the latter phenomenon is that the crystallization takes place in the bulk of the fluidized bed instead of near the wall. A super-cooling ice slurry generator type was experimentally tested and compared by Mouneer et al [37] with a traditional scraped surface type. A new method of ice slurry generation without the deposition of an ice layer on a cooled surface was developed by Koji et al. [38].

The recent review of the literature (as mentioned above) shows that there are broadly six methods used for ice slurry generation namely: (i) mechanical scraper method (also known as harvest method) (ii) fluidized bed method, (iii) direct injection method, (iv) vacuum freezing method, (v) oscillatory moving cooled wall method, and (vi) super-cooling water. The investment and operating costs of each of these methods is an important parameter during system selection procedure. In the mechanical scraper method the refrigerant evaporates in a double-wall cylinder. Through the inside space, bounded by the inner cylinder, the water or aqueous solution flows and the ice crystals are created. A rotary sharp edged scraper scrapes the ice growing on the cooling surface. The scraped surface generator has a large surface for the ice crystal creation per unit volume of ice slurry generator. In the fluidized bed method, the ice slurry generation process is performed using liquid–solid fluidized bed heat exchangers. In the direct injection method, the refrigerant is directly injected into the water domain. Liquid droplets of refrigerant enter through nozzles, normally at the bottom of the generator, and start to evaporate. The growing droplet/bubbles, moving upwards by buoyancy rise to the top of the water containing column. Vacuum freezing method has been investigated by ethanol solution and pure water. In the oscillatory moving cooled wall method, an oscillatory motion is applied to the cooled surfaces on which the ice layers are formed, and removed by the vibration generated during the oscillatory motion. In the super-cooling water method, the ice slurry is produced with low ice concentration by using a typical design of shell and tube type, but the initiation of the freezing should be controlled to adjust the produced ice concentration without system blockage. In the developing countries a widespread utilization of ice slurry systems for industrial applications has not taken place yet which is mainly attributed to the high investment costs of commercially available (only imported) ice slurry generators. The objectives of this study are design and fabrication of a small scale scraped surface ice slurry generator test rig through commonly used manufacturing processes employed by small and medium scale industries and collection of experimental data to understand ice crystallization mechanism in the microscopic scale, and heat transfer and fluid mechanics involving agitation and phase change in the macro scale for ice slurry production using Propylene Glycol (PG) and Mono Ethylene Glycol (MEG) water based solution at different solute concentrations. Experimental data have been collected on a prototype to explore the possibility for development of a future large capacity ice slurry generation machine.

II. EXPERIMENTAL SETUP AND PROCEDURE

In the present experimental study 'scraped surface ice slurry generator' of 5 liter capacity has been designed, developed and fabricated [refer Fig.1 (a) to (c)]. Experiments were carried out to collect the performance data for ice slurry production.

A. *Working Principle and Specifications of Scraped Surface Ice Slurry Generator*

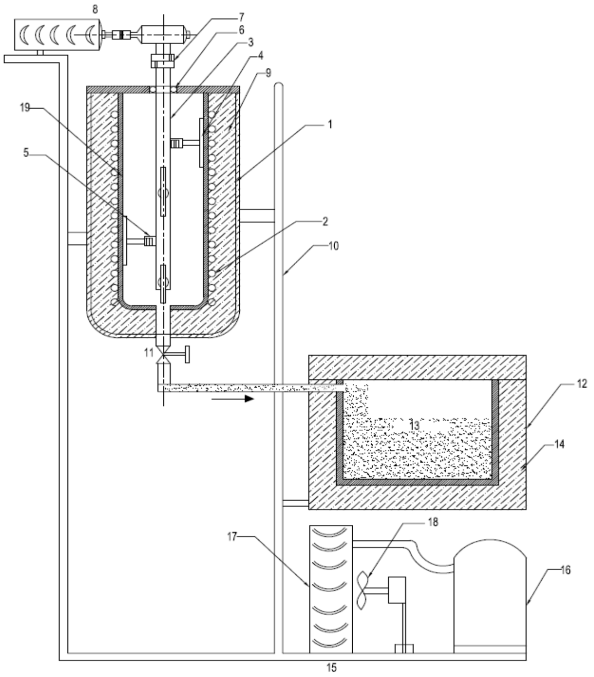

Fig.1 (a) Schematic diagram of Ice Slurry System

1 = Ice Slurry Generator
2 = Evaporator Coil
3 = Scraper Shaft
4 = Scraper Blade
5 = Spring
6 = Bearing
7 = Coupling
8 = Motor
9 = Insulation
10 = Frame
11= Valve
12 = Ice Slurry Tank
13 = Ice Slurry

14 = Insulation
15 = Condensing Unit
16 = Compressor
17 = Condenser
18 = Condenser Fan
19 = Inner Shell
20 = Soldering
21 = Refrigerant In
22 = Refrigerant Out
23 = Ice Slurry Out
24 = Ice Slurry Pump
25 = Cooling Load

The scraped surface ice slurry generator consists of a circular shell-and-tube type heat exchanger (Figure 2), where outer shell side is cooled by an evaporating refrigerant and inside surface is scraped by spring loaded rotating blades (Figure 3) to prevent any deposition of ice crystals on the cooled surface. This scraping action is required to prevent the formation of an ice layer on the inner walls of ice generator, which would otherwise introduce an additional thermal resistance and could seriously lower the heat transfer. The continuous accumulation of the ice layer on the ice generator walls would eventually block

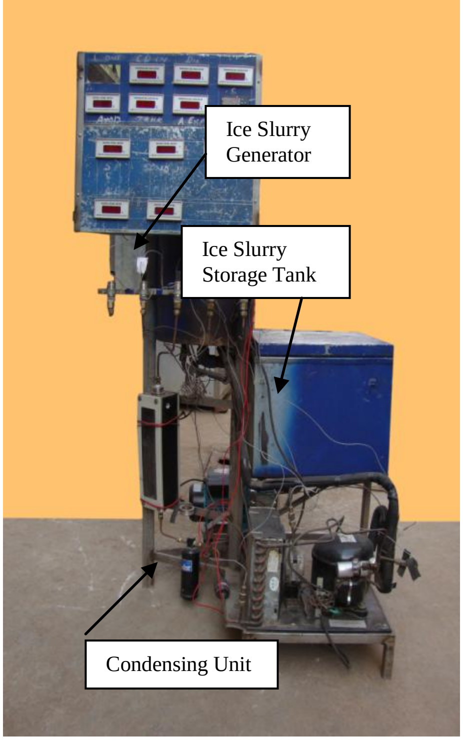

Fig.1 (b) Photograph of Ice Slurry System

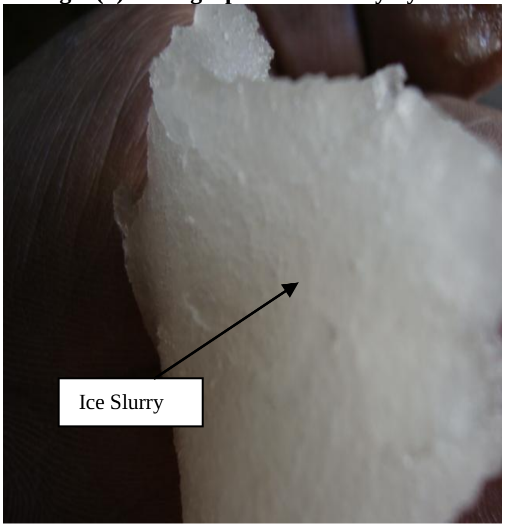

Fig.1 (c) Photograph of Ice Slurry

Rotation of the scraper blades and cause freezing up of the ice slurry generator. Depressants are added to depress the freezing point of the solution to prevent the freeze-up of the ice generator walls and alternatively provide impact on the temperature driving force for heat transfer. Turbulence is mechanically induced into the ice slurry flow by the action of the rotating scarper blades mounted in the centre of the heat exchanger, thus greatly increasing the heat transfer rates and facilitating the production of a homogeneous ice slurry mixture. Table 1(a) and (b) summarizes the specifications of the present ice slurry generator manufactured for laboratory purpose. Ice slurry generator is manufactured using stainless steel (SS304) tube. Stainless steel is the preferred material of construction because it offers good thermal properties, strength and corrosion resistance. Extruded materials can also be used to minimize the overall cost.

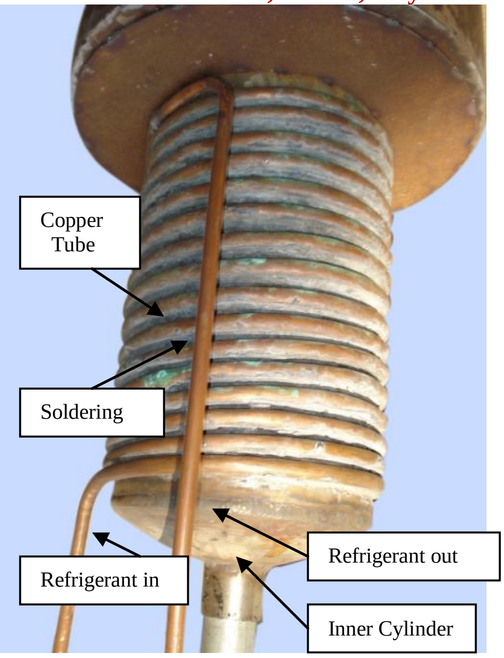

Fig.2 Photograph of coil of shell and coil type evaporator

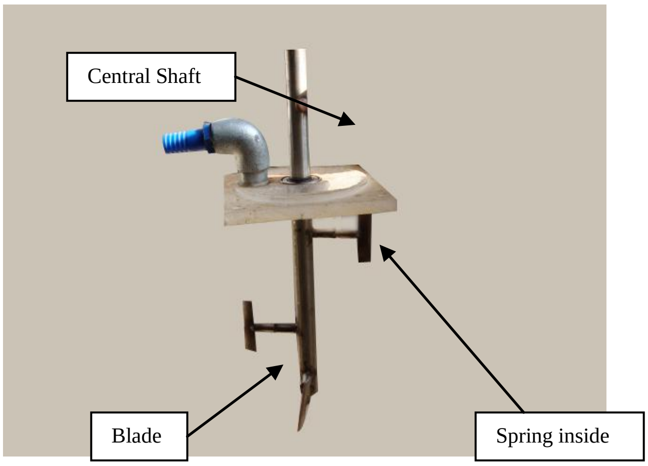

Fig.3 Photograph of Scraper blade assembly

Table 1(a): Specifications of ice slurry generator (including primary and secondary circuit components)

S. No.	Name of the component	Specifications(material/size)
1	Compressor	1/6 horse power
2	Condenser	Air cooled fin and coil type
3	Capillary tube	0.031 inch size
4	Evaporator	Circular shell and coil type of 3/8 inch coil
5	Inner cylinder	150 mm inner diameter (SS 304)
6	Scraper blade assembly	SS 304

7	Ice slurry tank	300 cubic mm (SS 304)
8	Ice slurry circulation pump	(SS 304), 1/4 horse power

Table 1(b): Technical specifications of ice slurry generator

Specifications	**The present design**
Ice slurry side	
Tube Material	304-Grade Stainless Steel
Evaporator type arrangement	Vertical
Freezing point depressant	Propylene glycol, mono ethylene glycol
Crystal size (mm)	0.2- 0.3
Inner tube diameter (m)	0.15
Tube length (m)	0.30
Heat transfer area (m^2)	0.1414
Agitation mechanism	SS 304 scraper blades 7.5 cm (L), 1.85 cm (W)
Agitation speed (rpm)	24
Refrigerant side	
Evaporator type	Circular shell and coil type of 3/8 inch coil
Refrigerant type	R134a

The stainless steel (SS 304) cylinder (150 mm inner diameter, 3 mm thickness and 300 mm length) is used as the main body for ice slurry generator. A copper tube (0.93 cm diameter) was wrapped in a spiral coil shape (16 numbers of turns) around the outer surface of the main cylinder (Figure 3). This copper tube is soldered with the outer periphery of the cylinder for proper contact to enhance the heat transfer effect. The total 40 feet length of copper tube was consumed. This type of copper coil configuration (evaporator) ensures proper turbulence for the primary refrigerant (R134a). Around the copper tube coil, polyurethane foam insulation of 7.5 cm thickness is provided and inserted between the inner and outer cylinders. The insulating material is compatible with the temperature of the cooling medium to minimize any heat gains from the surroundings. The two concentric cylinders are connected by welded neck flanged ends. The scraper blade assembly used in the present work consisted of four staggered spring loaded blades attached to the 25 mm diameter scraper shaft located centrally in the inner cylinder. Each blade is 75 mm long in the axial direction and 18.5 mm wide in the radial direction. An electric speed motor is mounted at the top of ice slurry generator to rotate the scraper shaft. The scraper blade assembly is coupled to electric motor (1 hp, 1425 rpm) via a reducing gear box of ratio 1:60 to provide rotational speed of 24 rpm to the scraper shaft. The rotational speed of the scraping mechanism was kept constant in all experimental observations presented herein this research which is the minimum speed with the lowest internal thermal resistance of ice layer formed.

B. *Experimental Setup*

A schematic diagram of the experimental apparatus is presented in Fig. 4. The present condensing refrigeration unit consisting of a compressor (1/6 hp, 1-φ, 230V, 50 Hz), air cooled condenser (fin and coil type 220 ×230 mm, 2 row deep, 3/8 inch diameter copper tubes, 6 fins per inch, fan 1300 rpm) and capillary tube (5/16 inch size having two 7 feet long passage) and measurement facilities. Ice slurry tank (300 mm×300 mm×300 mm size, insulated with 60 mm thick polyurethane foam) is connected with ice slurry generator through a ice slurry circulation pump (1/4 hp). This unit supplies the refrigerant to the coil of the ice slurry generator (referred as evaporator in the refrigeration cycle in Fig.4) where evaporating refrigerant at lower pressure

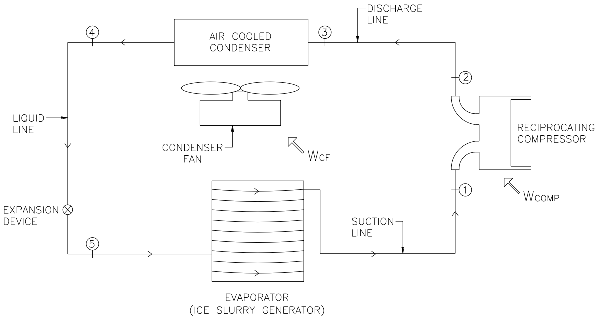

Fig 4 (a) Schematic of Direct-expansion, single-stage mechanical vapor compression refrigeration system of scraped surface ice slurry generator

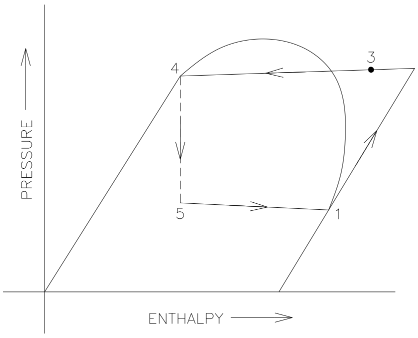

Fig.4 (b) Pressure-enthalpy diagram

Withdraws heat from the binary solution which is finally converted into ice slurry inside the generator. At the exit of the evaporator, a refrigerant vapor of enough superheat is generated from this indirect heat exchange process, recompressed and recompensed at high pressure to complete the refrigeration cycle. During the experimentation, ice slurries are made of an aqueous solutions of propylene glycol [PG] and mono ethylene glycol [MEG] having the initial weight concentration of 10%, 20%, and 30%, respectively.

C. *Measurements and Data Collection*

The temperatures at condenser inlet and outlet, compressor suction and discharge, ice slurry tank and ice slurry in the ice slurry generator were measured by resistance-temperature detectors with a range of -50 ºC to 0 ºC to 99 ºC and accuracy of 0.01 K. The pressures of primary refrigerant at condenser inlet and outlet, compressor suction and discharge, expansion outlet were measured using pressure transmitters with a range of 0 to 20 bar having accuracy of 0.01 bar. Mass flow rate of primary refrigerant was measured using rotameter. Propylene Glycol (PG) and Mono Ethylene Glycol (MEG) were used as additives **an** air-cooled, direct-expansion, single-stage mechanical vapor compression refrigeration system with R134a as primary refrigerant is used for scraped surface ice slurry generator. A pressure-enthalpy diagram of this system is shown in Fig. 4 (b). Table 2 (a) and Table 2 (b) summarizes the measured operating thermodynamic properties at inlet and outlet of various primary refrigerant components.

Table 2(a) Measured Thermodynamic Properties (MEG as Antifreeze in Ice Slurry Generator)

State	**Pressure (kPa)**			**Temperature (°C)**		
	10%	**20%**	**30%**	**10%**	**20%**	**30%**
1. Compressor suction	100	083	068	-6.9	-8.9	-12.0
2. Compressor discharge	1051	1005	985	46.7	45.7	42.1
3. Condenser inlet	1014	971	946	46.6	44.9	41.6
4. Condenser outlet	1005	961	939	36.3	35.5	35.4

5. After expansion	108	091	077	-7.0	-9.5	-12.1
6. Ice slurry temperature				-3.4	-7.1	-11.9

Table 2(b) Measured Thermodynamic Properties (PG as Antifreeze in Ice Slurry Generator)

State	**Pressure (kPa)**			**Temperature (°C)**		
	10%	**20%**	**30%**	**10%**	**20%**	**30%**
1. Compressor suction	104	082	062	-5.0	-8.7	-11.2
2. Compressor discharge	1045	1006	972	45.9	43.0	41.2
3. Condenser inlet	1010	972	935	45.8	42.6	40.9
4. Condenser outlet	999	962	929	35.7	35.3	35.2
5. After expansion	112	091	071	-6.8	-9.1	-11.5
6. Ice slurry temperature				-2.9	-6.4	-11.0

III. RESULTS AND DISCUSSIONS

The aqueous solution of antifreezes, Propylene Glycol (PG) and Mono Ethylene Glycol (MEG) with water at weight percentages 10%, 20% and 30% of antifreezes were used in the freezing process. The coolant temperatures were measured with resistance-temperature detectors. 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 (Figures. 5 to 7 for PG and Figures 8 to 10 for MEG) with respect to freezing time of ice slurry for PG and MEG, respectively. 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 slurry 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 Figures 5 to 7, the freezing temperature reduces with increase in antifreeze mass fraction for PG and MEG 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 8 to 10) 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. 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. With antifreeze PG, the lowest ice slurry temperatures achieved are -3.1 ^{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, -7.3 ^{0}C and -11.9 ^{0}C at 10%, 20% and 30% concentrations respectively.

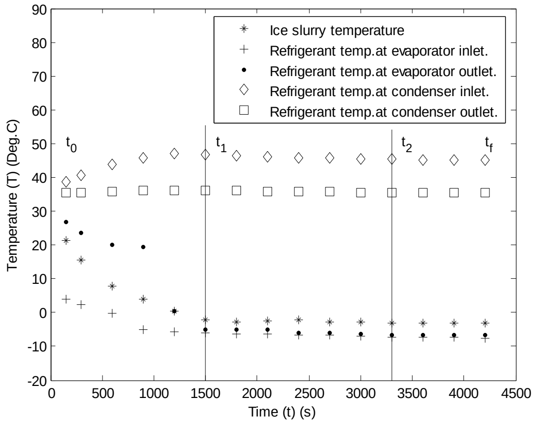

Fig.5. Freezing temperature vs time for PG at 10 % concentration

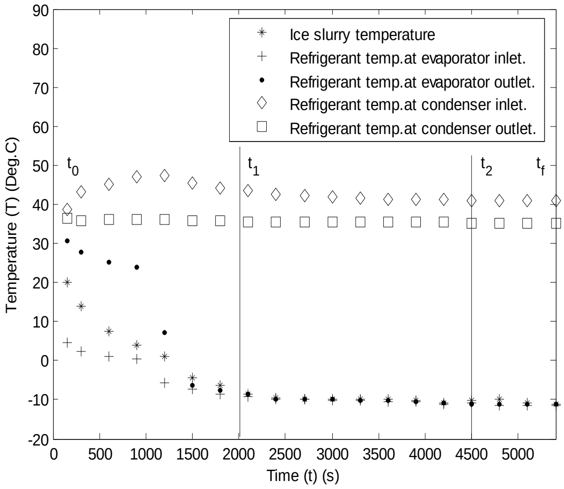

Fig.6. Freezing temperature vs time for PG at 20 % concentration

Freezing temperatures vs. antifreeze mass fraction is shown in Fig. 11. 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 (Figure 11). The 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.

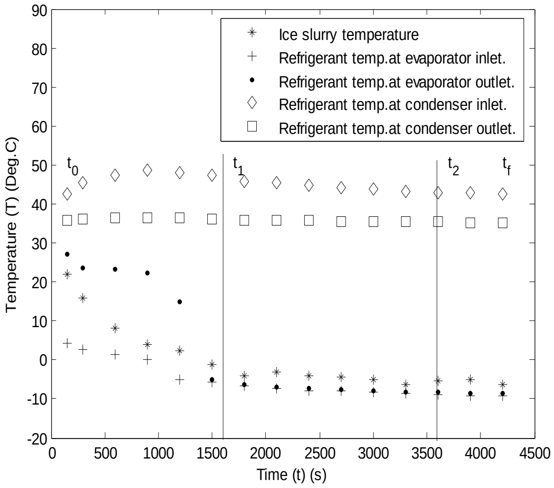

Fig.7. Freezing temperature vs time for PG at 30 % concentration

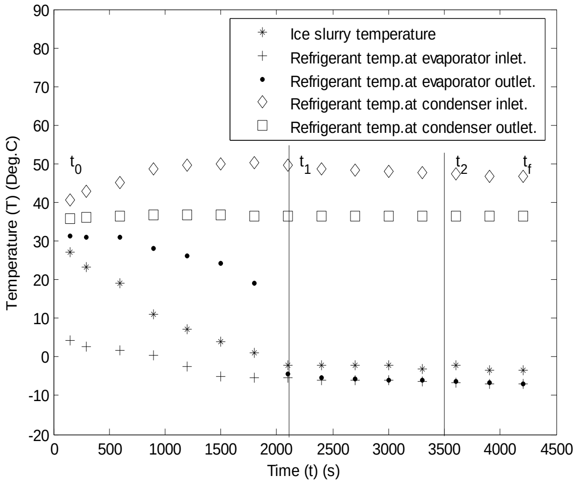

Fig.8. Freezing temperature vs time for MEG at 10 % concentration

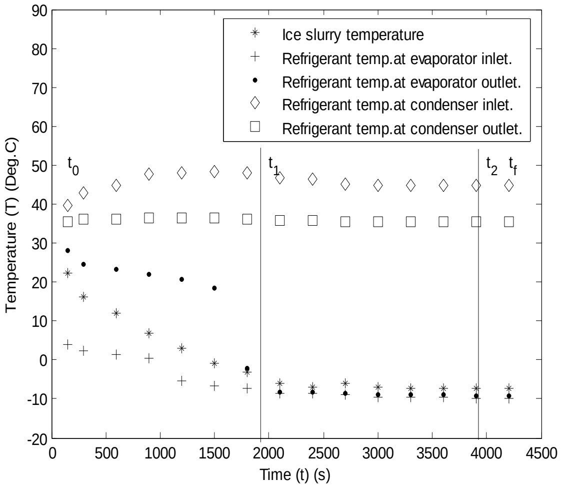

Fig.9. Freezing temperature vs time for MEG at 20 % concentration

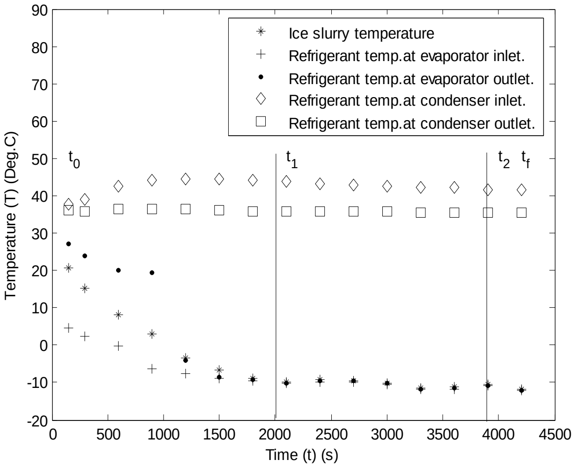

Fig.10. Freezing temperature vs time for MEG at 30 % concentration

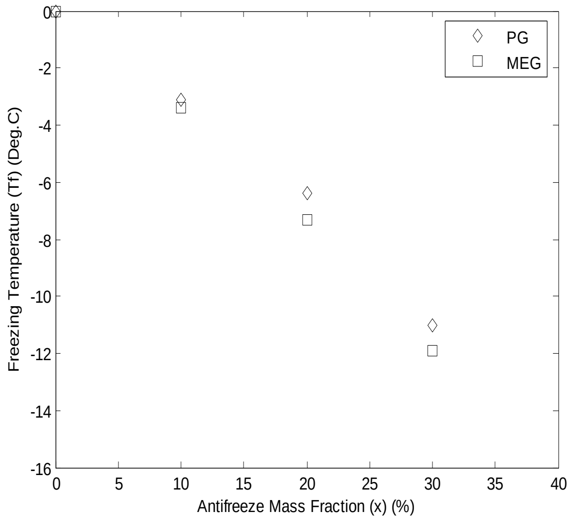

Fig.11. Freezing curve of water-PG and water- MEG mixture

Table 3 Thermodynamic heat and work calculations of Ice Slurry Generation System

	Concentration of PG			**Concentration of MEG**		
	10%	**20%**	**30%**	**10%**	**20%**	**30%**
Refrigerating Effect, N= h_1 - h_5 (W)	281.54	278.39	275.75	277.65	277.65	274.25
Compressor Work, W= h_2- h_1 (W)	58.10	60.18	61.74	61.49	63.23	63.80
Coefficient of Performance (COP=N/W)	4.84	4.62	4.46	4.55	4.38	4.29
Heat Rejected in Condenser, Qc=h_2-h_4 (W)	339.65	338.57	337.49	339.15	340.8419	338.05

Using the experimental data given in Table 2 (a) and Table 2 (b) thermodynamic heat and work calculations of Ice Slurry Generation System is shown in Table 3. For different concentrations of additives PG and MEG the COP of the system is between 4.29 to 4.84.

III. CONCLUSION

Following conclusions can be draw from the present research study:

1. A small scale scraped surface ice slurry generator test rig through commonly used cost effective manufacturing processes (employed by small and medium scale industries) is successfully fabricated for collection of ice slurry data. The present manufacturing technique can be extended for a higher capacity ice slurry generation machine suitable for industrial application.

2. Three distinct stages- cool down or chilling period, nucleation or unstable ice slurry generation period and stable ice slurry generation period were observed through historical time dependence curves.

3. The minimum ice slurry temperatures achieved are -3.1 ^{0}C, -6.4 ^{0}C and -11.0 ^{0}C at 10%, 20% and 30% PG concentrations, whereas with antifreeze MEG, lowest ice slurry temperatures achieved are -3.4 ^{0}C, -7.3 ^{0}C and -11.9 ^{0}C at 10%, 20% and 30% concentrations respectively.
4. It is observed that the freezing temperature reduces with increase in antifreeze mass fraction for PG and MEG.

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PATENTS

1, 'Efficient Split Desert Cooler'-Published in Indian Patent Office, Application Number: 1997/DEL/2012.
2, 'Scraped Surface Ice Slurry Generator/Machine'-Published in Indian Patent Office, Application Number: 513/DEL/2012.

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