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Design and Fabrication of Slurry Ice Generator

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Abstract: **This paper proposes the Design and Fabrication of a slurry ice generator which produces slurry ice, a mixture of water and ice wherein the ice is in the form of spherical crystals of about 0.1 to 1mm in diameter. It provides 3 to 4 times better cooling compared to flaked ice owing to larger heat transfer area. Slurry ice finds application in food preservation especially in the fishing industry. In India, flaked ice is used for seafood preservation. Introduction of slurry ice in the fishing industry will result in better quality of produce. This paper is focused on the design calculations and the selection of proper components wherein the conventional ice scraper is replaced by an Archimedes' screw to eliminate the use of circulation pump. The refrigeration system works on a simple vapor compression cycle. Ice crystals are formed on the inner surface of shell and coil type evaporator, and, scraped by the Archimedes' screw.**

Keywords* — *Ice Slurry, Archimedes' screw, Newtonian, pumpability, R134a, isentropic, coefficient of performance.

I. INTRODUCTION

The fishing industry in India makes use of flaked ice for preservation. Often times the quality of product received by consumer is lost due to various factors such as improper refrigeration due to flaked ice which promotes bacterial action. Slurry ice is found to cool the product at a faster rate and hence preserve it for longer durations so the quality is not compromised. Conventional slurry ice generators use vertical scraper blades for scraping and a centrifugal pump for circulation of fluid. The proposed design uses an Archimedes' screw type scraper which scrapes as well as circulates the fluid, eliminating the use of a pump. Ice could be produced in different form such as block, cube, flake ice which require a certain degree of manual operation for transportation from one place to another and owing sharp edges these results to poor heat transfer performance. However replacing normal flake ice with slurry ice will overcome all these problems and it is pumpable too. Need of pump in the existing slurry ice apparatus can be eliminated by using helical scraper with the concept of Archimedean screw.

Application of ice slurries can be grouped into 3 main categories: comfort cooling of office buildings and commercial and industrial facilities, food engineering applications and specialist future applications. In case of buildings, energy is stored during night and utilized during daytime to satisfy peak loads. In case of mine cooling slurry ice is found more satisfactory than water as temperatures remain constant by melting of ice. In fish cooling system fish is completely covered with slurries leaving no pocket. Ice slurries also perform efficient internal cleaning of pipes, ducts and heat exchangers. Ice slurries can also be pumped through veins and lungs to lower temperature much faster. Because of Pumpability slurry ice with nozzles can be used in fire extinguishing applications. With further research and development the number of applications is likely to increase.[4]

II. EXPERIMENTAL DETAILS AND DESIGN

A. Existing design of scraped surface ice slurry generator

The scraped surface ice slurry generator is currently the most technologically developed and widely accepted ice slurry generation process over the last 20 years. Traditionally scraped surface ice generators, also known as Scraped Surface Crystallizers (SSC), have been used by the chemical process industry for the separation of organic mixtures such as paraxylene from its isomers (orthoxylene, metaxylene, ethylbenzene). These crystallizers are typically longer (6–12 m) than the ice slurry generators with inner tube diameters ranging from 0.15 to 0.30 m, which are installed in series or parallel trains to achieve plug flow conditions. These SSCs typically require much lower scraping speeds (15–30 rpm) than the ice slurry generators necessary for separating the crystals from an incoming organic solution. The food industry has also used SSCs for cooling, slushfreezing, pasteurizing and crystallizing media that are viscous, sticky or particulates such as ice cream, frozen concentrated products, slush–ice beverages, margarine, butter, process cheese, chili, baked beans, meat and fish products. These crystallizers are technologically similar to the ice slurry generators.[2]

Working principle: The scraped surface ice slurry generator consists of a circular shell-and-tube type heat exchanger,

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cooled on its outer shell side by an evaporating refrigerant, and scraped on its inner side by spring loaded rotating blades or orbital rods to prevent any crystals from depositing on the cooled surface as shown in Figs. 1 and 2, respectively. This scraping action is required to prevent the formation of an ice layer on the ice generator walls, which would otherwise introduce an additional thermal resistance and could seriously lower the heat transfer.[2]

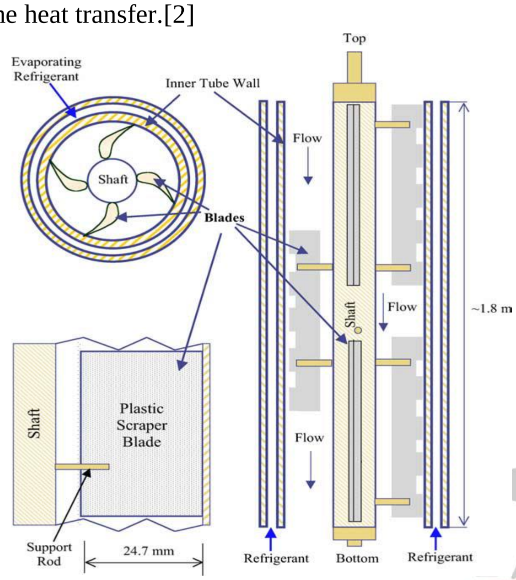

Fig. 1. Schematic of a scraped surface ice slurry generator.[2]

The continuous accumulation of the ice layer on the ice generator walls would eventually block rotation of the scraper blades and cause freezing up of the ice slurry generator. To prevent the freeze-up of the ice generator walls, solutes are added at concentrations less than the eutectic concentration to depress the freezing point of the solution but alternatively impact the temperature driving force for heat transfer. Turbulence is mechanically induced into the ice slurry flow by the action of the rotating scraper blades mounted in the center of the heat exchanger, thus greatly increasing the heat transfer rates facilitating the production of a homogeneous ice slurry mixture.[2]

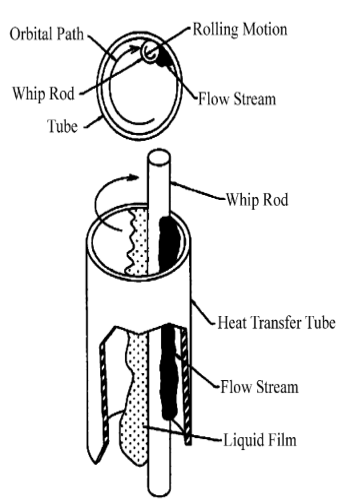

Fig. 2. Schematic of an orbital rod ice slurry generator.[2]

A condensing refrigeration unit, consisting of a compressor, condenser and an expansion device (such as a thermal expansion valve or capillary tubes), normally supplies the refrigerant to the shell-side of the ice generator, which is also referred to as the evaporator in the refrigeration cycle (see Fig. 3). As the refrigerant evaporates at a low pressure through the outer pipe of the ice slurry generator, it withdraws heat from its surroundings, cooling off the incoming binary solution (a dilute glycol or inorganic brine solution) flowing through the inner pipe of the ice generator (see Fig. 1). Using this cooling process, ice slurry is generated on the tube side of the ice slurry generator. The refrigeration unit may employ a liquid overfeed or flooded type scheme depending upon the application; however, it has been reported that flooded type refrigeration systems could cause the accumulation of oil lubricants on the evaporator side due to low temperatures involved and thus reduce heat transfer rates. At the exit of the evaporator, a refrigerant vapor of enough superheat is generated from this indirect heat exchange process, recompressed and recondensed at high pressures to continue the refrigeration cycle (see Fig. 3).[2]

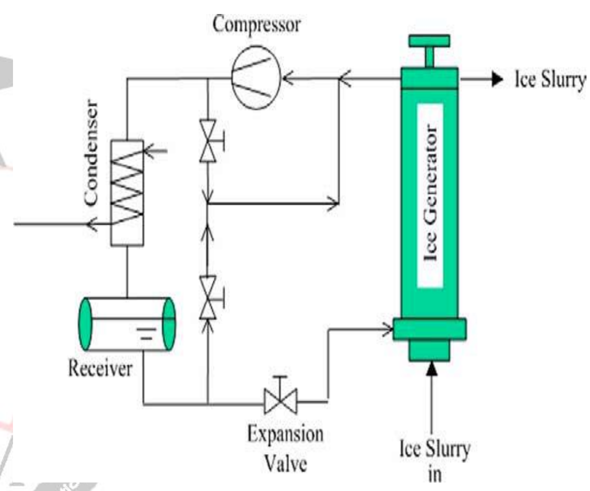

Fig. 3. Schematic of an ice slurry generation system.[2]

B. Construction: The setup consists of following parts

Refrigeration system: It uses a simple vapor compression refrigeration system wherein, refrigerant R134a is used. The primary components of refrigeration system are compressor, condenser, expansion valve and an evaporator.

The evaporator and scraper assembly: The evaporator is a shell and coil type evaporator where the brine solution flows through the shell and the coil is soldered around on the outside of shell. It also has a foam based insulation on the outside to minimize loss of refrigerating effect.

Archimedes' screw type of scraper: It is a helical structure with outside diameter equal to the inside diameter of shell. It scrapes ice and also circulates the solution.

Motor: A low rpm motor is used to rotate the screw

Storage tank: A tank with dimensions equal to the scraper assembly is used. It is also insulated.

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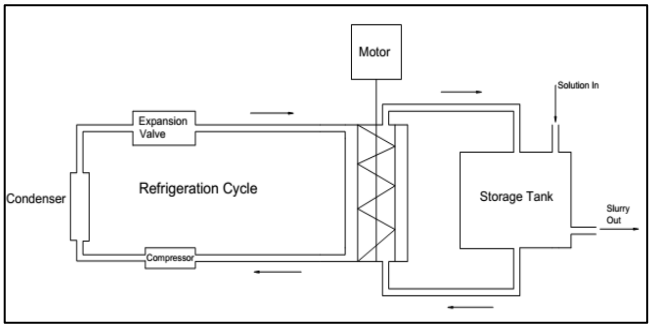

Fig 4. Block diagram of Slurry Ice Generator

C. Working

The storage tank along with scraper assembly will be filled with brine solution of known concentration. The salt concentration in brine solution will determine the ice concentration in the final product, slurry ice. The motor will rotate the Archimedes' screw type scraper at the speed of 30rpm which will circulate the fluid from storage tank at the rate of 0.3kg/s. The evaporator of the refrigeration system will keep the inside wall of scraper assembly at -10°C.

The temperature of brine solution will drop after each pass and eventually, ice crystals will form on the inner surface of the scraper assembly cylinder. These crystals will be scraped off by the scraper and will be mixed thoroughly with the rest of the solution. After a certain fixed time, desired concentration of ice slurry will be obtained.

D. Thermodynamic Model

Assumptions:

To obtain an initial design, the following assumptions are made:

- The four components (compressor, condenser, evaporator, thermal expansion valve) of the thermodynamics cycle are modeled as open systems.
- The four components (devices) operate under steady-state, steady-flow process.
- The changes in kinetic and potential energies across each device are negligible.
- Both the compressor and the expansion device are considered adiabatic (i.e. the heat transfer from these devices is negligible).
- Both the evaporator and the condenser are considered constant pressure devices.

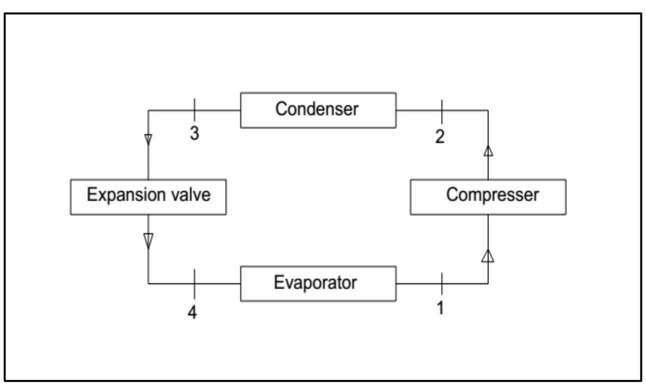

Fig 5. Vapour Compression Refrigeration Cycle

The basic concept of this design is to use a vapor compression cycle. Utilizing the first and second laws of thermodynamics along with the above mentioned assumptions, a thermodynamics model for the refrigeration system can be developed as follows:

Compressor: $W_c = \dot{m}(h_1 - h_2)$ (2.1)

Condenser: $Q_{out} = \dot{m}(h_2 - h_3)$ (2.2)

Evaporator: $Q_{in} = \dot{m}(h_1 - h_3)$ (2.3)

Expansion valve: $h_3 = h_4$ throttling process

Where W is the power input to the compressor, $\dot{m}$ is the mass flow of the refrigerant, Q_{in} is the heat absorbed by the evaporator, Q_{out} is the heat rejected by the condenser and h is the enthalpy. In these relations the number refers to the state of the refrigerant as indicated (see Fig. 5).

The isentropic efficiency of the compressor, η, is defined as the ratio of the isentropic (ideal) work input required to the actual work input required for the same inlet state and the same exit pressure:

$$\eta = \frac{h_1 - h_{2t}}{h_1 - h_{2a}} \quad (2.4)$$

The coefficient of performance (COP) for the refrigeration system is given by:

$$COP = \frac{Q_{in}}{W} \quad (2.5)$$

E. Refrigerant selection

For an effective system, a refrigerant should be used to ensure necessary thermodynamic properties at the temperatures and conditions the system will be operating at, and to ensure increased efficiency. To determine which refrigerant to use, several factors should be considered. The refrigerant should not be toxic, it should not be flammable at the operating pressures and temperatures, it should be minimally environmentally degrading, and in general, it should not be harmful to humans.

Based on an intensive review and search of several refrigerants such as R-12, R-22, R-134a, R-410a, and ammonia, it was found that R-134a is a safe, non-toxic refrigerant that is easy to obtain. Thus, it was selected to be the working fluid for this refrigeration system.

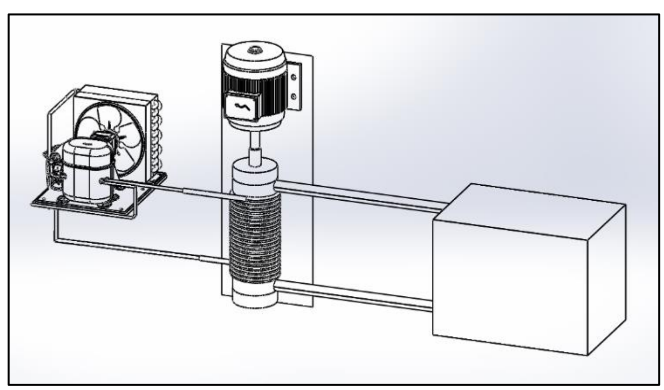

Fig 6. Schematic of Slurry Ice Generator

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III. Design And Fabrication

Table 1 : List of Components.

Component	Description	Material
Compressor	$\frac{1}{6}^{th}$ hp single phase hermetic compressor	-
Condenser	Air cooled fin type with 300 W heat rejection	Copper
Evaporator	Shell and coil type. Coil dia. $\frac{5}{16}^{th}$, 9 turns. Shell inner dia. 10 m, 3 mm thickness, length 20 cm. Coil soldered to shell.	Copper, 304 grade stainless steel
Throttle valve	Operating between 12 bar and 1.5 bar	
Storage tank	360m × 200mm × 300mm	Polystyrene
Scraper	Archimedes' screw type. Length 20 cm, pitch 8 cm.	Mild Steel
Scraper motor	$\frac{1}{4}^{th}$ HP motor. Speed reduced to 30 rpm.	

IV. Observations

Pressure on High side = 175 psi = 12 bar
Pressure on low side = 20 psi = 1.5 bar
Quantity of Water = 6.25 kg
Quantity of Salt Added = 200 g
Total mass of brine Solution =6.45 kg

Table 2: Observation Table

Time in minutes	T_1 in °C	T_2 in °C	T_3 in °C	Water Temperature in °C
0				30
10	16.5	45.3	34.6	17.4
20	15.7	43.6	34.7	12
30	14.2	42.9	34.7	8.2
40	13.3	42.4	34.8	5
50	10.4	42.4	34.7	2.5
60	8.5	42.1	34.7	0.5
70	7	41.5	34.5	-0.8
80	5	41.6	34.7	-1.3
90	4.2	41.6	34.5	-1.6
100	4.2	41.8	34.6	-1.4
110	3.7	41.2	34.1	-1.3
120	3.9	41.4	34.4	-0.9
130	3.9	41.5	34.8	-0.8
140	3.7	41.6	35	-0.6

V. Calculation

Table 3 : Taking reading at 90 minutes.

Time in minutes	T1 in °C	T2 in °C	T3 in °C
90	4.2	41.6	34.5

At pressure 1.5 bar $H_1 = 406$ KJ/Kg K
$S_1 = 1.809$ KJ/Kg K
Specific Density $= 6.957\ kg/m^3$
At pressure 12 bar saturation condition $T_2' = 46.316$ °C
$H_2' = 422.215$ KJ/Kg
$S_2' = 1.7092\ KJ/Kg\ K$
$C_{pv2}' = 1.1783$ KJ/KgK at point 2'

$$S_2 = S_2' + 2.3 \times C_{pv2}' \times \log\left(\frac{T_2}{T_2'}\right)$$

$T_2 = 347.573$ K
$H_2 = H_2' + C_{pv2}' \times (T_2 - T_2')$
$H_2 = 455.51$ KJ/Kg
$H_{f3} = H_{f3}' - C_{pl3} \times (T_3' - T_3)$
$H_{f3}' = 265.90$ KJ/Kg
Cpl3 = 1.5412 KJ/Kg K
$H_{f3} = H_4 = 247.68$ KJ/Kg

$$COP = \frac{(H_1 - H_{f3})}{(H_2 - H_1)} = 3.197$$

Refrigeration Capacity of the system:
$RE = m \times (H_1 - H_{f3})$

$$= \frac{0.0876}{60} \times (406 - 247.68) = 0.2311\ KW$$

$$RE = \frac{0.2311}{3.5} = 0.066\ TR$$

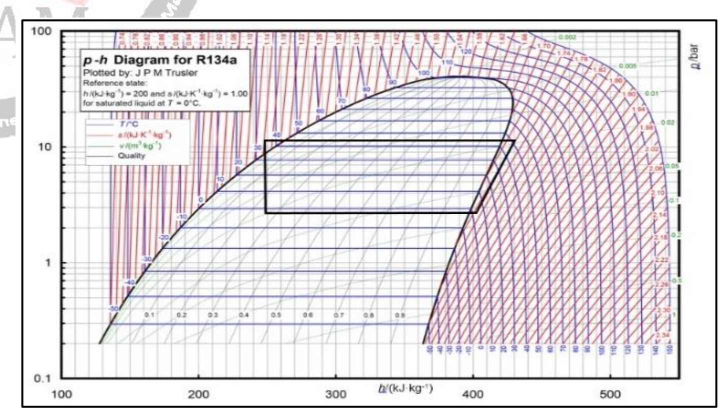

Fig. 7. P-h Diagram for R134a[8]

Time Calculation:

Refrigeration Effect = Heat loss by Water

$$0.2311 = 4.08 \times 6.45 \times \frac{(32 - (-1.6))}{Time}$$

Calculated Time = 63.74 min
Observed Time = 90 min

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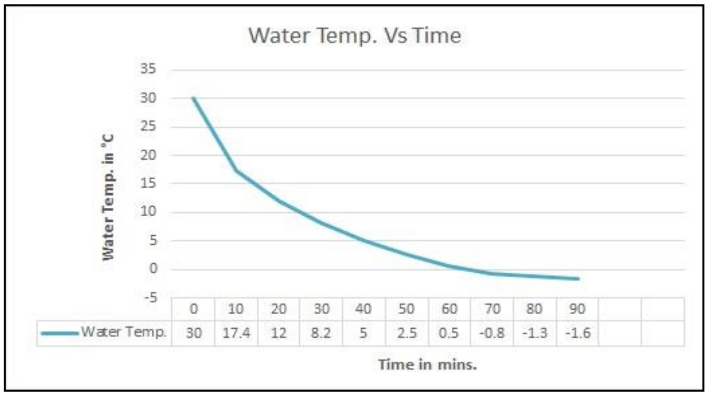

Fig. 8. Graph of Water Temperature vs Time

VI. Conclusion

This paper illustrates the design and fabrication of slurry ice generator with its innumerous advantages. A small scale slurry ice generator was successfully designed and fabricated from which the above mentioned results has been obtained. Various concepts of heat transfer, refrigeration and strength of materials were used in the process of designing.

The fabricated setup takes less than 90 minutes to make 8 liters of slurry ice. The minimum temperature attained by slurry ice was -1.6^{0}C. The difference between calculated time and actual time taken for slurry formation is 27 minutes which is fairly close considering acute rise in surrounding temperature and overall efficiency of the system. The coefficient of performance of system is 3.19 with a refrigerating capacity of 0.066TR.

The ice slurry generator can be introduce in the Indian market owing less power consumption due to elimination of circulating pump.

VII. Future scope

- Scientific study on performance of slurry ice with respect to its ice fraction.
- Scientific study on performance of slurry ice by changing the anti-depressant used.
- Scientific study on losses during pumping of ice slurry.

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