DEVELOPMENT AND STUDY OF RETROFITTED STANDALONE SOLAR VAPOUR ABSORPTION REFRIGERATOR

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Abstract- Vapour Absorption Refrigeration Systems (VARS) are thermally activated cooling systems which can be run using waste process heat or solar energy. VARS are environment friendly and operates silently. This study attempts to convert a commercially available VARS into a standalone, portable solar-operated unit. Temperatures at the entry and exit of Generator, Rectifier, Condenser, Evaporator and Absorber in a commercially available VARS refrigeratorwere first obtained. The refrigerator is then retrofitted with a heating jacket. A hot fluid is passed through the jacket to replace the electric heating in the conventional refrigerator. The fluid is heated using a parabolic trough solar collector. Laboratory simulation of the collector was conducted using an immersion heating coil and data were recorded using commercial software LabVIEW 2010. Although temperatures obtained by the retrofitted system were equivalent to those produced by the electric heating, the time taken to attain the respective temperatures was too long to be technically viable. Sufficient wattage was also generated by the solar collector for attaining these temperatures. The heat flux generated by the present setup was not sufficient to activate the internal thermosiphon used to circulate the refrigerant and hence there was no cooling effect.Thus the use of a solar heating system on a VARS with a thermosiphon unit may not be a technically viable proposition to make it a standalone system.

Keywords: *Solar collector, Vapour Absorption Refrigeration system, Thermosiphon.*

I. INTRODUCTION

The objective of this project is to develop and study a Solar-powered Vapour Absorption Refrigerator. A commercially available absorption refrigerator is non-intrusively retrofitted with a Heating Jacket to which heat is supplied from a parabolic solar collector. The present study is a socially conscious, eco-friendly attempt to make refrigeration available at places where conventional refrigeration is infeasible due to infrastructure or economic reasons.

Two major problems facing India today are electricity shortages and lack of food security. Firstly, the power deficit has been growing steadily since 2003[9][6]. India may face electricity shortage of over 10 per cent in 2012 as fuel scarcity and environmental issues have hit the power sector. The anticipated energy and peaking shortage in the country would be 10.3 per cent and 12.9 per cent, respectively (in 2011-12) according to the Central Electricity Authority. Going by the projections, there would be an electricity supply shortfall of 96,367 million units in 2011-12, and the requirement is expected to be higher at 933,741 million units as against an estimated availability of 837,374 million units [6]. Secondly, according to data released by Geo-Heat Centre Quarterly, 75-80% of fruits and vegetables perish every year due to inadequate cold storage and food processing facilities.The study attempts to address these issues by providing refrigeration using solar power. It will also help reduce electricity consumption and carbon footprint. Vapour absorption technology has been frequently adopted for solar refrigeration. It requires very low or no electric input and, for the same capacity, the physical dimensions of an absorption refrigerator are smaller than those for adsorption refrigerator (but larger than vapour compression systems) due to the high heat transfer coefficient of the absorbent. VARS using current absorption technology [2] can provide COPs ranging from 0.3 to 1.2. Choice of an absorption cooling refrigerator is primarily dependent on the performance of the solar collector to be used. For solar collectors capable of efficiently working at around 150°C, double-effect LiBr–water chillers with COPs around 1.2 are available for air conditioning. For refrigeration, ammonia–water chillers with COPs around 0.8 can be considered. The heat transfer medium can either be a liquid with a high boiling point or steam.

Other technologies like the S.T.E.V.E.N Icemaker [13] makes use of an absorption cycle but the refrigeration happens in intermittent cycles. Such technologies store the heat of the sun during the day and provide the refrigeration effect at night.

II. EXPERIMENTAL SETUP

A. Dometic RH440- LD

The Dometic RH440-LD is a commercially available VARS refrigerator.It uses the absorption refrigeration pair of water and ammonia[1]boosted by Hydrogen for its operation.Pentene gas is employed for insulation purposes. It has a capacity of 40 litres and consumes

65W of electric power. The heat required by the refrigerator is provided by a cylindrical heater which has been welded externally to the generator pipe.

B. Energy Source

In this section, various ways to supply heat to the generator pipe of the VARS are discussed. Since the entire refrigeration cycle is hermetically sealed, any heating had to be done externally on the generator pipe.

1) Heating Element of the Refrigerator

The stock refrigerator uses a cylindrical electric element 8.7cm long. This is attached to the generator pipe using a line weld join using a sheet of metal to enhance thermal contact. Most of the 65W of electrical power supplied to the refrigerator is consumed by the heating element.

2) Immersion Coil

To simulate the solar collector in the laboratory, an immersion type water heating coil was used to heat the circulating fluid to the required temperature. The coil consumes 1KW of power and was immersed in the thermal reservoir.

3) Solar Collector

Based on the data collected during the experiments in the lab, the solar collector was designed and fabricated. The solar collector was constructed using acrylic mirror sheet and uses a copper pipe as the generator.

C. Thermal Reservoir and Piping

To ensure consistency of operating temperatures for the refrigerator, uniform heating needed to be achieved. Since this was not practical with solar heating directly, an intermediate thermal reservoir was used to buffer the changes in solar insolation and to provide a near-constant temperature for the circulating fluid.

A vessel made of GI sheet was used as the reservoir. Metal nipples were provided for entry and exit of the fluid circulating in the heating jacket. Connections were made using braided polymer pipes/mild steel pipes depending on the fluid and operating temperature being used at the time.

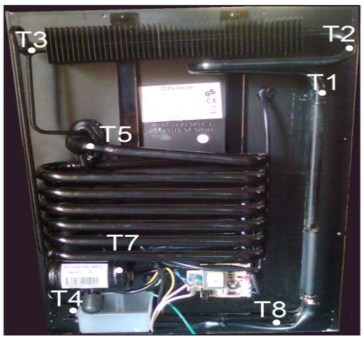

Figure 1: Placement of Thermocouples

D. Heating Jacket

Since only external methods could be employed to heat the generator pipe, a heating jacket was designed and fabricated specifically to suit the spatial limitations and the heating requirements. Surface area was maximized by using a metal clamp to ensure the generator pipe was being heated from all directions.

E. Heat Transfer Medium

Initially, water was used as the heating medium.But since water boils at 100 °C, it could not provide the desired heating effect.Refined sunflower oil was then chosen as the heat transfer medium since it can be used to attain temperatures as high as 360 °C without flashing. It is also cheap and easily available.

F. Data Acquisition System

To perform a complete performance analysis of the stock refrigerator as well as the refrigerator after retrofitting, ten thermocouples were mounted at different points of the cycle on the refrigerator. K type thermocouples were used since they offer sufficient accuracy and are the most suitable for the range of temperatures (up to 1100 °C). The thermocouples were mounted at the following points as shown in Fig.1:

T1: Generator Outlet; T2: Rectifier Outlet; T3: Condenser Outlet; T4: Absorber Outlet; T5: Absorber Inlet; T6: Ambient; T7: Vessel; T8: Generator Inlet; T9: Evaporator; T10: Refrigerator Chamber

A state of the art, NI-9213 16 channel thermocouple data acquisition board was used to acquire signals from the thermocouples. The NI-9213 is exclusively a temperature acquisition module with support for various types of thermocouples. It also has built in cold junction compensation so it need not be done externally. A *LabVIEW* interface was created to display all the temperatures at any time. All the temperature data was also written to a file for later analysis.

III. COMPONENT DESIGN AND SYSTEM TESTING

A. Analysis of Stock Refrigerator

Fig.2 shows the rear view of the stock refrigerator, before any changes were made to it. Fig. 3 shows the working cycle with fluid flows of the Dometic RH 440-LD refrigerator.

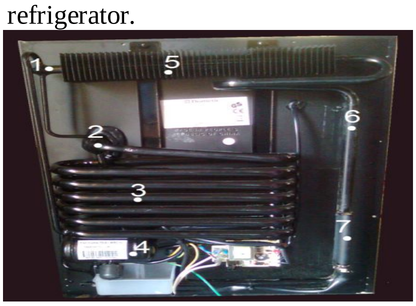

Figure 2: Rear View of Refrigerator without Insulation

1. Hydrogen enters the pipe with liquid ammonia
2. Ammonia + hydrogen enter the inner compartment of the refrigerator (Evaporator). Change in partial pressure causes ammonia to evaporate. Energy is being drawn from the surroundings - this causes the cooling effect Ammonia + hydrogen return from the inner part, ammonia returns back to absorber and dissolves in water. Hydrogen is free to rise upwards
3. Ammonia enters the absorber
4. Absorber Vessel (water + ammonia solution)
5. Condenser
6. Water Separator
7. Heat source (electric)

The stock refrigerator was run continuously from a cold-start for a period of three hours and temperatures at various points in the cycle were measured and recorded using K type thermocouples and NI-9213 DAQ. Temperatures at the generator outlet and refrigerator chamber are plotted against time. A sampling rate of 0.1Hz (one sample every ten second) was used for the measurement of the refrigerator temperatures.After a period of three hours, the refrigerator temperatures become steady and the refrigerator operates with slightly varying temperatures depending upon the thermostat setting.

The data was obtained using *LabVIEW 2010* and the temperature variations with time were plotted using *Origin Pro*. These observations have been elaborated below. With this data, an idea of the requirements for the next step was obtained.

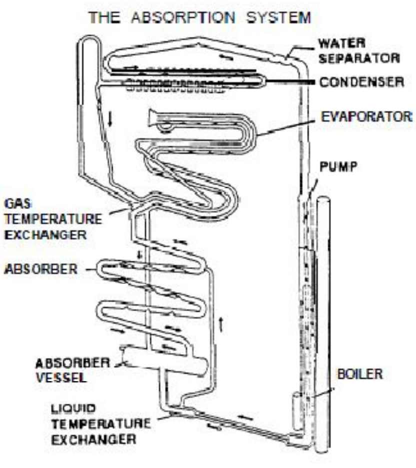

Figure 3: Schematic of VARS [4]

B. Heating Jacket

A heating jacket was used to transfer the heat obtained from the solar collector to the generator of the VARS. Due to spatial limitations that come with the refrigerator, a standard heat exchanger apparatus could not be used here and the heating had to be done in a non-intrusive manner. The jacket used was designed intuitively. The requisite mass flow rates of the working fluid and other parameters were refined using trial and error.

For the maximum utilization of the available space, the design shown below was used. A CAD model of the heating jacket is also shown below, in Fig. 4.

The material used for the jacket isa galvanised iron sheet. One sheet of metal was bent in the shape of a half-cylinder cut along its axis, with its diameter equal to that of the section of piping behind the heating element on the refrigerator. Another sheet was cut elliptically with the length of the major axis larger than the diameter of the smaller sheet, and placed over it. The lateral ends of the sheet were then welded together, with two covers (lids) placed on the ends, which were subsequently welded. Gas cutting was employed to cut the covers to the required shape. Hose nipples were attached 2.5 cm from either end of the Jacket, and the circumferential line of contact between the nipple and the Jacket was welded as well, to ensure the entire setup was leak-proof.
The jacket now comprises of two parts:

- The heating section
- The clamping section

The heating section was the one through which hot fluid from the collector was passed. The working fluid from the solar collector was first sent to a thermal reservoir. This ensures a regulated and constant temperature of the generator throughout the day. If the collector was to be connected directly to the jacket, then the generator temperature would vary from a maximum of around 110°C in the midday to ambient temperature when sunlight was unavailable. This was unacceptable for the cycle operation. The clamping section was primarily to secure the heating section of the jacket. A small amount of heat transfer takes place between the two sections due to conduction. The two sections are joined together over the generator pipe using four pairs of self-tapping sheet metal screws.

The heating jacket acts like a parallel flow heat exchanger. The hot working fluid was then circulated through the heat jacket for the operation of the refrigerator. Again, due to spatial and orientation limitations, other and theoretically more efficient configurations could not be used.

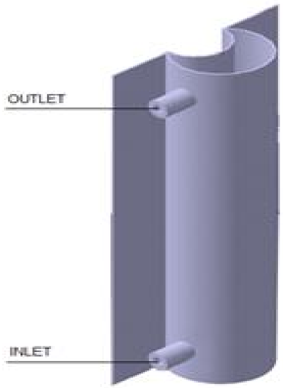

Figure 4: CAD Model of the Heating Section of the Retrofitting Apparatus

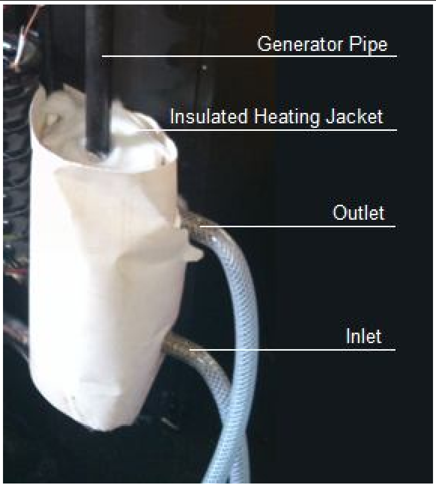

Figure 5: Position of the Heat Exchanging Jacket

To prevent heat losses to the atmosphere by convection, the jacket was insulated. This was done by tightly covering the setup with glass wool and wrapping it with paper subsequently. The view of the jacket after insulation is shown in Fig. 5.

C. Simulated Run using Immersion Coil Heater and Heating Jacket

The retrofitting apparatus or heating jacket was attached to the generator part of the VARS. The leads of the actual heater used in the refrigerator were disconnected from the circuit board. The jacket was properly insulated with glass wool, to minimize heat losses to the atmosphere.

To analyse what temperatures would be needed for the circulating fluid, a simulated experiment was connected with the heat jacket in place and the fluid being heated by an immersion coil, instead of the solar collector. Mass flow rate of the circulating fluid was controlled using a globe valve.

Initially, hot water was used as the fluid medium to transfer heat. This was a serious limitation as fluid temperatures of above 80 °C were hard to obtain and maintain due to the high specific heat capacity and low boiling point of water.

Hence, oil was chosen as the next choice of circulating fluid. Oil offered many advantages over water, the most important of them being a much wider range of operating temperature. Refined sunflower oil was used for this purpose as it was easily available and retains its properties at high temperatures (over 300 °C). Also, it was observed that the viscosity of the oil dropped significantly at high temperatures which allowed it to flow easily through our siphon system.

5 litres of refined sunflower oil was heated in a reservoir using the immersion coil and circulated through the heating jacket. It was observed that the use of braided polymer hose restricted the fluid temperatures as it started melting close to temperatures of 210 °C. To overcome this limitation, a rigid circulation setup was fabricated using mild steel pipes joined by welds. Care was taken to ensure that all components were leak proof. The use of steel pipes permitted the use of very high temperatures effectively eliminating one of the most important limitations.

With the rigid steel piping, sufficiently high temperatures were attained to obtain refrigeration. Results have been discussed in Chapter 4.

Fig.6 shows the experimental setup as a whole.
1: *LabVIEW* Interface
2: *NI-9213* DAQ
3: *Dometic RH 440 LD*
4: Thermal reservoir

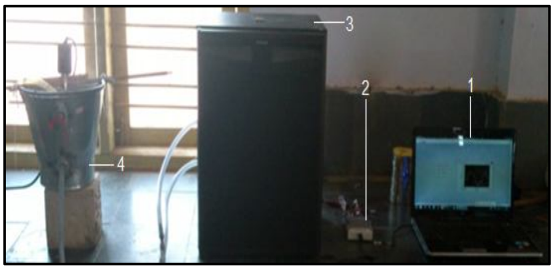

Figure 6: Experimental Setup

D. Solar Collector

1) Concept

A parabolic trough solar collector uses a mirror in the shape of a parabolic cylinder to reflect and concentrate solar radiations towards a receiver tube located at the focus line of the parabolic cylinder. A fluid runs through the copper tube along the length of the focus of the parabolic trough and gets heated from solar insolation.

2) Construction

In Fig. 7, 1 is the back plate, 2 is the end plate, 3 is the cover, 4 is the receiver, 5 is the bearing, 6 is the end angle of the cover, 7 is the side angle of the cover, 8 is the side angle of the back, 9 is the reinforcement bar of the end.

Manufacturing of a parabolic trough generally involves using metal forming processes at high temperatures to create a parabolic shape. This is known to be expensive and complex[8] [16]. Moreover, precision is hard to achieve using this method. The method used here exploits the natural elasticity of a one-sided acrylic mirror sheet to form the parabolic shape. Minor adjustments to give higher precision were done using redressing mechanisms. The major advantages of using this technique were low costs, simplicity in construction and its performance was sufficient for the intended applications. The parabolic profile was marked on the acrylic sheet and was cut out. Another sheet (measuring 0.9144m by 1.2192m) was made to fit this profile that had been traced and was clamped using L-Angles. Redressing bars were fixed along the length of the collector to provide rigidity and support. Redressing was also provided along the sides of the collector to ensure that the collector always retained its parabolic shape[16]. These redressing strips on the sides were provided with screws which could be tightened or loosened as required.

The profile of the parabola was obtained using the software *Parabola Calculator*, as shown below in Fig. 8. This was used to fabricate the end plates of the solar collector.

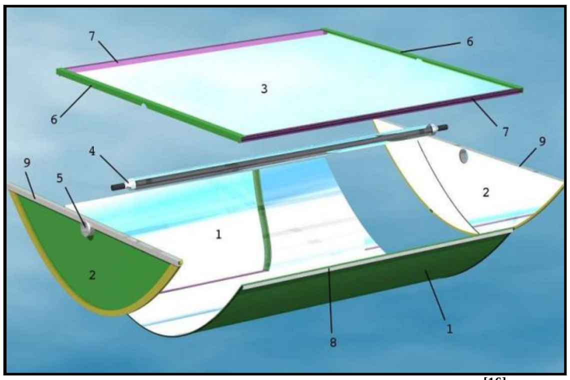

Figure 7:Exploded View of the Solar Collector[16]

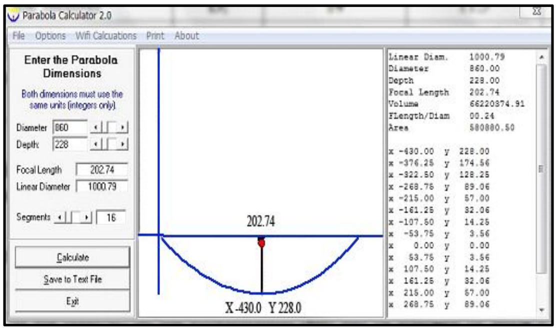

Figure 8: Parabola Calculator Showing Coordinates

3) Analysis

For theoretic analysis of the solar collector, solar insolation was assumed to be 900W/m^2 which is close to the average maximum value of solar insolation received by the district of Dakshin Kannada, Karnataka[12].

4) Calculations

To calculate the wattage of the solar collector, water at 35 °C was passed through the collector at full flow rate at a head of about one metre.

Solar energy received by collector area= Area of the collector × insolation
= 0.9144m×0.9906m× 900W/m^2
= 0.906m^2× 900 W/m^2
= 815.4W

Assuming reflectivity of the mirror sheet to be 0.95 and the transmissivity of the acrylic cover to be 0.90,

Theoretical wattage of the solar collector = Total energy x 0.95 x 0.90
= 815.4 × 0.95× 0.90
= 697.17 W

Thermosiphon[15]is a method of passive heat exchange based on natural convection, which circulates liquid without the necessity of a mechanical pump.Its intended purpose is to simplify the pumping of liquid and/or heat transfer, by avoiding the cost and complexity of a conventional liquid pump. A thermosiphon[15] system was set up to circulate the fluid between the thermal reservoir and the collector. A schematic of a thermosiphon is shown in Fig. 9.

The heat stored in this reservoir is intended to be used to drive the heating jacket. The thermosiphon system is preferred here as the pump required to drive high temperature fluid is expensiverendering the system economically infeasible

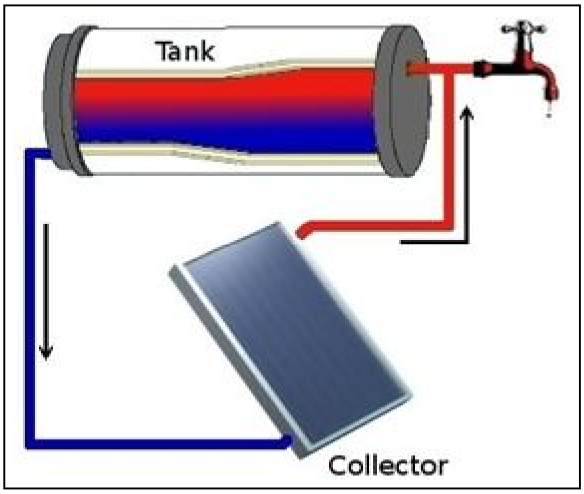

Figure 9: Schematic of a Thermosiphon System used for Circulation

Figure 10: Thermal Collector with Thermosiphon Circulation

Fig. 10 shows the collector with the thermosiphon set up. In Fig. 10,

1. Base
2. Bearings
3. Thermosiphon Reservoir
4. Braided polymer pipes
5. Copper pipe, Diameter 1.27cm
6. Transparent Acrylic Cover

IV. RESULTS AND DISCUSSION

A. Stock Refrigerator

Fig. 11 shows the variation of generator and chamber temperatures with time. The generator outlet temperature at this steady state is found to vary around the value of 110 °C, and the temperature at the outlet of the rectifier stabilized at around 44 °C. The generator and rectifier temperatures become stable in 33 minutes, and chamber temperature of near zero is attained in slightly over 3 hours. These temperatures were taken as our benchmark and target temperatures after the retrofitting apparatus was in place.

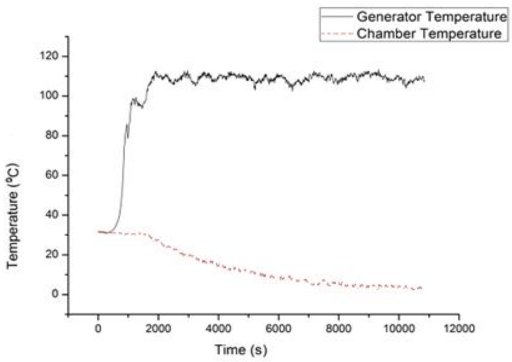

Figure 11: Graph showing variation of Generator and Chamber Temperature with Time

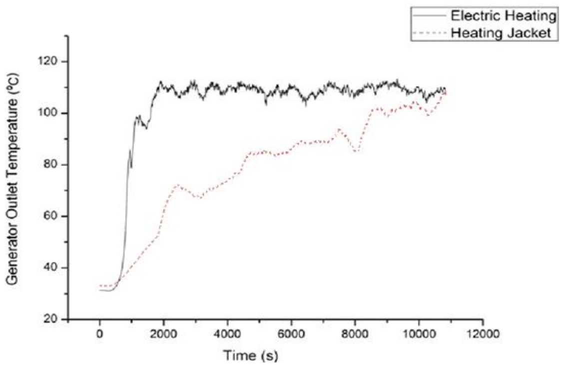

Figure 12: Graph showing comparison of Generator outlet Temperatures (a) with Electric Heating and (b) with Heating Jacket

B. Simulated run using Immersion coil

When the refrigerator was run using water heated by an immersion coil, steady temperatures of 50°C at the outlet of the generator were obtained. These were far from the results obtained in the stock refrigerator trial.

Hence, oil was chosen as the next choice of circulating fluid. Oil offered many advantages over water, the most important of them being a much wider range of operating temperature. Refined sunflower oil was used for this purpose as it was easily available and retains its properties at high temperatures (over 300 °C). Also, it was observed that the viscosity of the oil dropped significantly at high temperatures which allowed it to flow easily through our system.

It was observed that when fluid temperature was maintained at 280 °C, a steady temperature of 110 °C and 44 °C could be obtained at the outlet of the generator and rectifier respectively. However, obtaining this temperature took 2 hours, 47 minutes as compared to the rapid heating done by the electric heater (in 33 minutes). Fig. 12 shows the comparative temperature growth rates between the electric heater and the retrofitting apparatus.

This proved that sufficient heat could be provided and the required temperatures could be attained using the heating jacket to run the refrigerator. However, cooling could not be achieved as the heat flux was insufficient for boiling of Ammonia required for running the refrigerator continuously. The service manual of the refrigerator shows the design of the thermosiphon pump which forms a part of the generator pipe. For this pump to function effectively, a very high heat flux is required, which is not attainable by exchanging heat with a hot fluid. Electric heaters are very effective in heating applications since higher temperatures are obtained resulting in higher rates of heat transfer.

However, exceeding temperatures of 300 °C for the circulating fluid is not practical as it leads to difficulties in handling of the fluid (pumps, pipes, etc.) Generating temperatures of over 300 °C is possible using solar collectors but construction becomes complex and expensive. This is because very accurate foci are required to obtain the required concentration ratios to attain the said temperatures. Pumps for handling such hot fluids are also very expensive, rendering the set up economically infeasible.

C. Solar Collector

The solar collector was tested and its performance studied. Inlet and outlet temperatures were found in each case using mercury in bulb thermometer.

1) Single Pass Wattage

For water passing through a collector only for a single pass, temperatures of 42 °C were obtained in the afternoon with the water initially at a temperature of 35 °C.

A temperature rise of 7 °C was obtained when the flow rate was 1.4 kg/min.
Heat absorbed by the water = $m \times c \times \Delta T$

= (1.4 × 4200 × 7) / 60 = 686W
The efficiency is found to be 84.17%

2) Closed Circulation

For a reservoir capacity of 5 litres, a uniform temperature of 75 °C was obtained from water at 35 °C, after running the collector for 30 minutes.

Heat absorbed by the water = m×c×ΔT
= (5 × 4200 × 40) / (30 × 60)
= 466.6W

The efficiency of the system is found to be 57.22%
This drop in efficiency is seen due to the heat lost to the atmosphere from the reservoir and circulating system, and lower heat transfer rates at higher temperatures.

V. CONCLUSIONS

The effect of replacing the electric heating in a VARS with a solar energy source was studied experimentally. The following conclusions can be drawn from the study:

- It is possible to achieve the requisite Generator and Rectifier temperatures of 110 °C and 44 °C respectively with the Heating Jacket.
- The internal thermosiphon system used to circulate the refrigerant cannot be activated using the present setup, which in turn led to no cooling effect.
- Attaining these temperatures took 2 hours and 47 minutes, which is longer in comparison to the electric heating in the stock refrigerator.
- Successful operation of the cooling cycle requires a precise amount of heat flux to be supplied at the exact location of the electric heating element.
- Difficulty in fluid circulation and hazards associated with handling of fluid at temperatures beyond 300°C in the reservoir inhibit the practical use of this setup.
- Thus the use of a solar heating system on a VARS with a thermosiphon unit may not be a technically viable proposition to make it a standalone system.

VI. FUTURE SCOPE

In the future, design of the Heating jacket can be improved to obtain better heat transfer. Technologies like Micro-channel Heat Exchangers can be used in place of the Heating Jacket for compact and effective heat transfer. Fluids with lower specific heat capacity and higher convective heat transfer coefficients can be employed. Similar studies may be undertaken on VARS that do not employ a thermosiphon for refrigerant circulation.

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