# INVESTIGATION AND PERFORMANCE ANALYSIS OF HYBRID SOLAR POWERED WATER HEATER AND ADSORPTION REFRIGERATION SYSTEM

A Thesis submitted to Gujarat Technological University

for the Award of

**Doctor of Philosophy**

in

**Mechanical Engineering**

by

**Hiteshkumar Anilkumar Bhargav**
Enrollment No. 119997119002

under supervision of

**Dr. Bharat M. Ramani**

**GUJARAT TECHNOLOGICAL UNIVERSITY**
**AHMEDABAD**

**MARCH – 2018**

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# Abstract

Heating and Cooling is one of the important and required application at present. It is also estimated that more than 25% of the power consumed in water heating and cooling technologies throughout the world. Both technologies affect ecology in direct as well indirect ways. The Indian government has already initiated and installed solar thermal collectors for different applications (MNRE installed - 7 million square meters area solar thermal collector). Solar water heaters are widely used for residential and industrial water heating applications. It is observed that these solar water heaters are effectively used for 5-6 months in a year and for the remaining period they remain idle during summer, considering Indian climatic conditions. Therefore in this work, an attempt is made to utilize solar water heaters for cooling application by a novel thought. The cooling effect can be produced by utilizing the same solar infrastructure during summer. The substantial amount of vegetable, food and fruit are wasted at farm site due to unavailability of local preservation facilities. The cost of preserving food at cold storage enhances the overall cost for producer and consumer.

Solar cooling technology is a boom in non-electric grid area where the spoilage of food, medicine, and milk occurs. The Adsorption refrigeration system has advantages like operated by low-grade heat (solar energy, waste heat, biomass heat, etc.), eco-friendly working pair, the absence of vibration and load sensitive design (fraction TR to hundred TR capacity). In solar cooling technology, solar powered adsorption refrigeration system has potential to compete with other non-conventional cooling technology, i.e. Absorption, PV based, Waste heat driven and Biogas cooling technology. The solar-powered hybrid water heater and adsorption refrigeration have been designed, developed and analysed in the present study for receiving the dual advantages.

Solar powered adsorption refrigeration systems preserve the food for the national requirement and also protects the environment. Adsorption Refrigerator works on physio sorption or chemisorption principle. In physio sorption, weak wander walls bonds can easily break by low generation temperature. A cooling effect in physio sorption-based refrigerator can produce by

adsorption and desorption of adsorbate (refrigerant) over adsorbent through the thermal compressor.

The present research work is comprised of three parts, identification of best working pair by developing adsorption capacity measurement facility/equipment, Development of semi-continuous adsorption chiller powered by the conventional solar water heater and identification of best working environment through series of experiments.

- The adsorption capacity measurement equipment is developed by considering isobaric adsorption phenomenon in which system pressure and evaporator temperature remain constant through varying adsorption temperature. This equipment is used to estimate the adsorption capacity of three working pairs namely activated carbon fibre-methanol, activated carbon fiber-ethanol and activated carbon pallet-ethanol. The experiment was conducted using a stainless steel adsorber, 110 mm diameter by 150 mm height, filled with adsorbent material and transparent plastic evaporator, 100 ml capacity, filled with adsorbate. The experiment was performed by isobaric adsorption in the temperature range of 10-100º C at the evaporator temperature of 20°C (water chiller). Experimental investigation showed that activated carbon fiber- methanol pair has highest adsorption capacity (0.44 kg/kg) compared to activated carbon fiber- ethanol and activated carbon pallet- ethanol pair. To correlate adsorption characteristics, the Dubinin-Astakhov equation is used. The finding is exposed that uniform structure and large surface area of adsorbent, additionally low boiling point and large latent heat of adsorbate produce a significant effect on adsorption capacity. The effect of time and adsorber temperature on adsorption capacity is also discussed in this study.
- Two types of adsorption refrigerators are reported based on their working cycles one is intermittent and other continuous). The Intermittent and Continuous solar powered adsorption water chiller have their advantages and limitations. In this research study, a semi-continuous solar powered adsorption water chiller for food preservation has been investigated. The design of the main components includes an adsorber bed, a condenser, an expansion device and an evaporator. This has been performed by fundamentals of energy and heat transfer equations with adsorption science.

- To identify the best working environment of the semi-continuous solar power adsorption water chiller, series of experiments have been performed by varying different parameters like hot water temperature, cold water temperature, a flow of water, condenser temperature, time of supply (hot water and cold water) etc. During experiments, drop in temperature of water available in the evaporator is observed as a cooling effect. The important performance parameters SCP and COP are obtained by cooling effect and electric input to the water heater. The cooling effect produced in 10 kg of water was 554 kJ in 6 hours with a water flow of 170 kg/hour, condenser temperature of 25° C and adsorber temperature of 65° C. The fluctuation in system pressure was observed in the range of 30 kPa to 80 kPa for desorption and adsorption process during experimentation. For experimental purpose, the electrical heater is used in a water tank to simulate solar-powered water heater. This arrangement gives controlled temperature and flexibility throughout the experimentation schedule. The mass of activated carbon fiber (ACF) is 450 gram, and charged methanol is 650 ml, which helps to reduce the size of an adsorption chiller. It was discovered from the parametric analysis that desired cooling effect is produced with low generation temperature (60- 65°C) which can attain by the conventional solar water heater.

The chiller performance was tested and compared with the adsorption chiller already reported. The comparison shows that proposed chiller has higher specific cooling power (SCP), low cycle time and low generation temperature due to activated carbon fiber-methanol pair and effective design of the system. The proposed solar-powered hybrid water heater and adsorption refrigeration system is very useful for the preservation of food at farm site and reduces dependency regarding cold storage and the conventional cooling system operated by electricity. This chiller also has potential to operate with waste heat or biomass (farm waste) by devoted design.

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At the outset, I would like to express my heartfelt gratitude towards my guide and mentor **Dr. Bharat M. Ramani** (Supervisor), Professor and Principal, Shri Labhubhai Trivedi Institute of Engineering and Technology, Rajkot for guiding me throughout the journey of the doctoral research. He has been the continuous source of motivation and inspiration. Thank you will be the very small word against the knowledge and compassion he bestowed throughout.

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**Hitesh Bhargav**

**Research Scholar, Gujarat Technological University**

# Table of Content

# List of Abbreviation

| Abbreviation | Full form |
|---|---|
| A | Heat transfer area ($m^2$) |
| AC | Activated carbon |
| ACF | Activated carbon fiber |
| ACP | Activated carbon pallet |
| BET | Brunauer, Emmett and Teller |
| ºC | Degree Celsius |
| Cp | Specific heat (kJ $kg^{-1}$ $K^{-1}$) |
| CPC | Compound parabolic concentrators |
| COP | Coefficient of performance |
| Cu | Copper |
| D | Inside diameter of tube (m) |
| DA | Dubinin and Astakhov |
| DR | Dubinin and Radushkevitch |
| $D_{cap}$ | Capillary bore |
| $D_e$ | Shell side equivalent diameter |
| $D_o$ | Outside diameter of tube |
| dT | Temperature drop in water |
| $dT_m$ | Temperature difference in methanol |
| ETC | Evacuated tube collector |
| FPC | Flat plate collector |
| G | Mass velocity |
| GWP | Global Warming Potential |
| h | Convective heat transfer coefficient |
| h’ | Enthalpy |
| hg | Mercury |
| i | Inside |
| k | Thermal conductivity (W $m^{-1}$ $K^{-1}$) |
| L | Length of pipe (m) |
| LMTD | Log mean temperature difference |
| $m_{ref}$ | Mass of Methanol (kg) |
| $m_w$ | Mass flow rate of water (kg $s^{-1}$) |
| $h_{fg}$ | Latent heat of methanol |
| $m_{ads}$ | Mass of ACF(kg) |
| $m_m$ | Mass flow rate of methanol(kg $s^{-1}$) |

| | |
|---|---|
| MNRE | Ministry of New and Renewable Energy |
| $NH_3$ | Ammonia |
| Nu | Nusselt number |
| o | Outside |
| ODP | Ozone depletion potential |
| Q | Heat flux (kW) |
| Pr | Prandtl number |
| R | Resistance to heat transfer |
| Re | Reynolds number |
| SCP | Specific cooling power ( kJ/kg) |
| T | Temperature (K) |
| TEMA | Tubular exchanger manufacturers association |
| u | Free stream velocity of the fluid ($m\ s^{-1}$) |
| UG | Under Graduate |
| UV | Ultraviolet |
| v | Specific volume |
| x | Adsorption capacity (kg of methanol / kg of ACF) |
| $\rho$ | Density ($kg\ m^{-3}$) |
| $\Delta P$ | Pressure drop |
| $\Delta L$ | Incremental length of capillary tube |
| $\mu$ | Dynamic Viscosity |

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# CHAPTER 1

# Introduction

Indian culture as well as around the globe, it is accepted that sun is a source of all the form of energy. All form of energy is directly or indirectly derived from solar energy. In India Sun is considered as a god and people are worshipped to thou. Also for meditation and yoga, "SURYA NAMASHKAR" is considered as the best technique for internal peace and physical health. It is concluded from the law of energy conversion that one form of energy can be converted into another form of energy and the Clausius statement of the $2^{nd}$ law of thermodynamics states that the expenditure of energy can produce the cooling. In vapour compression refrigeration system (VCRS), compressor work and in vapour absorption refrigeration system (VARS), heat is utilized for production of cooling. It is established that solar energy can be utilized for several applications like water heating, power generation, drying, cooking, space heating & cooling, process heating etc.

It is estimated that more than 25% of the power is consumed in water heating and cooling technologies throughout the world [1]. These technologies affect ecology in direct as well indirect ways. The rising price of fossil fuel and ecology problems has again drawn attention to look for reliable, pollution free and cheap refrigeration technology. Indian government already installed solar collector for different applications (MNRE installed - 7 million square meters area solar thermal collector). Solar water heaters are idle during summer. By utilising the same infrastructure, one can produce cooling during summer. Solar cooling technology is a boom in non-electric grid area where the spoilage of food, medicine, and milk occurs. In solar cooling technology, solar powered adsorption refrigeration system has potential to compete with other non-conventional cooling technology, i.e. Absorption, PV based, Waste heat driven and Biogas cooling technology. Solar powered adsorption refrigeration system utilises the total solar radiation (UV, Visible and Infrared) for producing refrigeration effect. In Adsorption refrigeration system, cooling can be produced by adsorption/ desorption phenomenon powered by low-grade heat, solar energy, waste heat or biogas heat. Ultimately with this system cooling can be produced by clean energy or waste heat which assist in reducing conventional fuel consumption and maintain zero GWP /ODP.

In summer, solar energy is ample which satisfies the need of cooling in the same season. The solar-powered cooling machine could only be used in season. Hence it is expensive than the conventional cooling machine which can be used for the whole year. The requirement of cooling and heating of household is noted the same as and when the season changes. Single solar powered heating or cooling machine cannot meet the need of household throughout the year. In proposed research work, hybridizing the solar water heater with adsorption refrigerator is performed for achieving dual advantages throughout the year. By this concept of dual-purpose system, one can reduce pay-back period by half. In this research work semi-continuous solar powered Adsorption water chiller is planned to develop for cooling of 10 kg water in 3 hours with a temperature drop of 10° C by hot water available at 65 to 75° C.

Solar powered adsorption refrigeration systems have preserved the food for the national requirement and also protected the environment. Solar powered adsorption refrigeration system uses natural refrigerant and operates at low generation temperature which can be achieved by a flat plate collector. This system uses very low intrinsic parts which can be operated with no or little electricity. Adsorption Refrigerator works on physio sorption or chemisorption principle. In physio sorption, weak wander walls bonds can easily break by low generation temperature. A cooling effect in physio sorption-based refrigerator can produce by adsorption and desorption of adsorbate (refrigerant) over adsorbent.

The main drawback of adsorption cooling is lower COP and higher thermal mass. Solar based cooling systems are intermittent due to nature of availability of solar energy. To develop a continuous cooling system, energy storage or double bed must be designed which ultimately adds to extra cost and equipment. The solar-powered hybrid system of the water heater and adsorption refrigerator is suited for a remote location without firm electricity supply. It is powered by solar thermal energy. Therefore, they are silent in operation. It will be useful for medicine, vaccine, food preservation in rural areas. One can directly install this system for village milk collection centre for preserving milk for some duration.

Various working pairs are available for adsorption refrigerator which includes silica gel-water, zeolite-water, activate carbon-ammonia, barium chloride-ammonia etc. The selection of working pair depends on the accessible heat source, cooling requirement and existing space. The working pair has various properties like desorption temperature, working pressure, and adsorption capacity. For refrigeration applications, ACF-methanol pair has potential as a working pair due to its better adsorption characteristics. The adsorption capacity of working pair is measured by protocol development. For technology development, the best suitable working pair is decided by adsorption isotherm and kinetics of the pair. In present work, the adsorption capacity of a different working pair has been measured for selecting the best pair for the water chiller. For Adsorption capacity, the test set-up has been developed, and experiments were performed in the range of temperature 15-80°C with isobaric adsorption.

An adsorption chiller is thermally driven refrigeration system operated by solar energy or waste heat. The construction is similar to vapour compression refrigeration system except for thermal compressor. Other components like evaporator, condenser and expansion device are same. Due to the porous structure of adsorbent, refrigerant from the evaporator is adsorbed at low temperature and pressure which produces a cooling effect. Adsorbed mass of refrigerant is desorbed by supplying heat to adsorbent material and adsorbed by providing low temperature to the adsorbent. In this way, the intermittent cycle is operated, and cooling is produced by providing periodically heating and cooling the adsorber bed. Isobaric adsorption and desorption with temperature swing operation in adsorber bed produce the refrigerating effect. Fig.1.1 shows the schematic diagram of semi-continuous adsorption chiller operation and Fig.1.2 represent the Clapeyron diagram for the thermodynamic cycle.

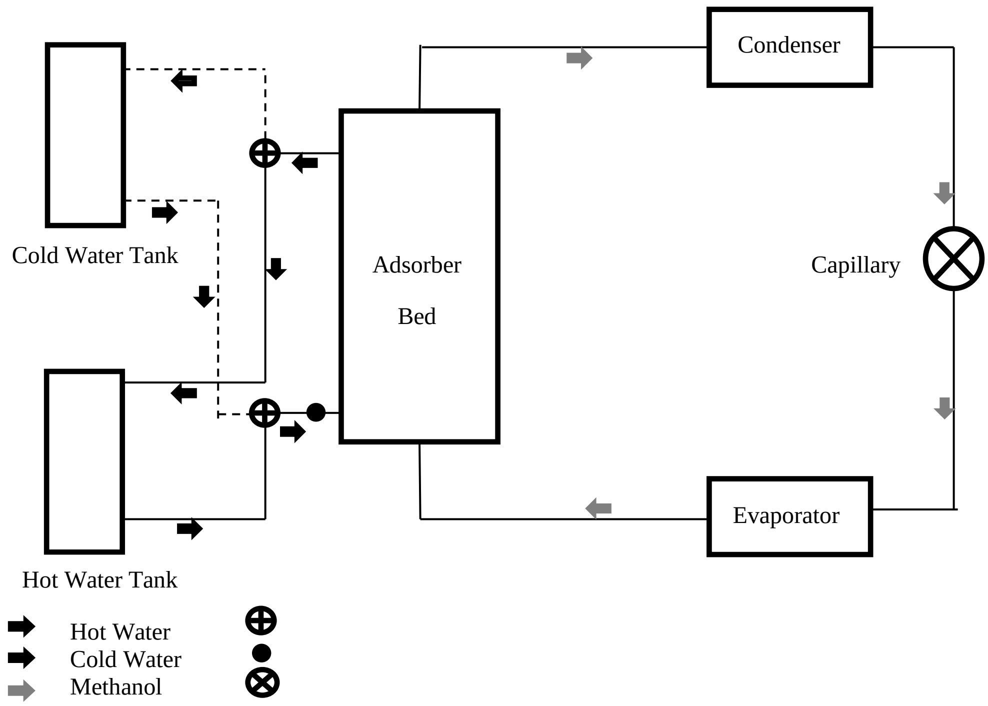


**Figure 1.1 Schematic of adsorption chiller operation**

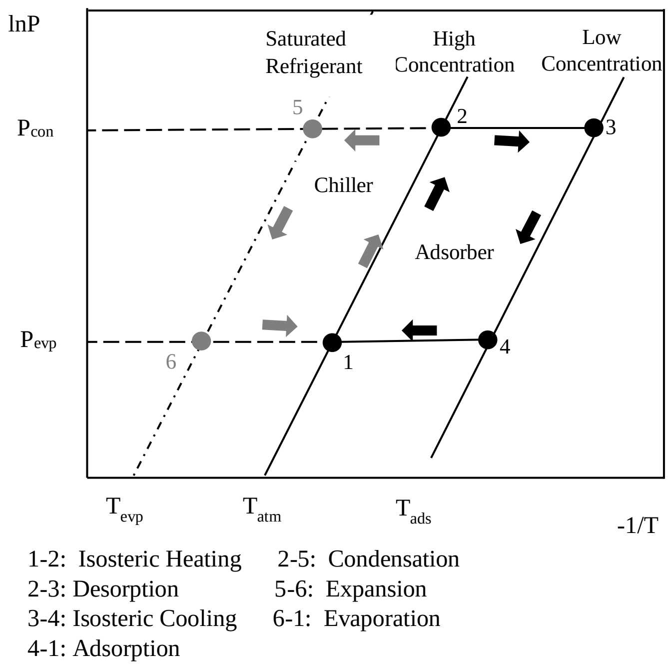


**Figure 1.2 Clapeyron diagram for the adsorption chiller thermodynamic cycle [2]**

There are two types (intermittent and continuous) of cycles available in adsorption refrigerator. The Intermittent and Continuous solar powered Adsorption water chiller have their advantages and limitations. Due to the nature of solar energy, an intermittent system has been developed by the researcher for getting better synchronization between refrigerator and availability of solar energy. This will not satisfy the cooling requirement like food preservation, vaccine storage, space cooling and water chilling which needs lower cycle time. The continuous adsorption system requires double or multi adsorber bed, pumps and better refrigerating & hydraulic circuit design which ultimately add complexity & overall cost to the system.

## 1.1 Definition of the Problem

*"Hybridizing of the solar water heater with adsorption refrigerator can satisfy the cooling requirement of the water chiller."*

## 1.2 Objective and Scope of work

From the literature, it is inferred that intermittent cycle solar adsorption refrigerator have large cycle time, more adsorbent mass, poor SCP and lower COP. The continuous cycle needs special attention regarding multi-bed, hydraulic circuit and pumps. Hence optimization of the intermittent and continuous cycle, the Semi-continuous cycle is proposed with following objectives.

### Objectives

- To study and investigate the best working (adsorbent- refrigerant) pair for adsorption water chiller system through adsorption capacity measurement.
- To design and develop semi-continuous adsorption water chiller and to carry out experimentation for investigating best environment.
- To identify the range of hot water (generator) temperature for determining the type of collectors through parametric analysis on adsorption water chiller.
- To investigate the effect of generator (hot water) temperature on COP and SCP of adsorption water chiller through series of an experiment.
- To identify best working environment ( system pressure, hot/cold water temperature, time of hot/cold water supply and condenser water temperature) for better performance of system through series of experiment

**Scope of work**

- ACF-Methanol as a working pair
- Temperature drop of 10° C in 10 kg water in 180 minutes through Semi-continuous system
- Design and develop shell & tube type adsorber bed, immersed coil evaporator, and water cooled condenser
- Simulation of a solar water heater by hot water tank with an electric heater.

## 1.3 Preliminary Investigations were done

Literature survey submitted that more focus is on activated carbon pallet or powder as an adsorbent for adsorption chiller. This form of activated carbon does not give satisfactory results in adsorption refrigeration system. Also, major adsorption chiller is working on intermittent cycle which has inherent limitations. It was the plan to develop a semi-continuous system with adsorbent as activated carbon fibre (ACF) and methanol as a refrigerant. For the feasibility of work is checked by developing laboratory scale for final year UG project. The laboratory scale model gave expected results in refrigeration laboratory. Fig.1.3 shows the laboratory scale model of adsorption refrigerator using ACF as an adsorbent. In this model, 7ºC drop in the evaporator is observed in 8 hours with 10 gm ACF and 30 ml methanol. The operating parameters are 70ºC hot water temperature, 30ºC cold water temperature, 15-minute heating, 10-minute cooling, and flow rate of water was 5 ml/sec. It confirmed that semi Continuous system produced a cooling effect.

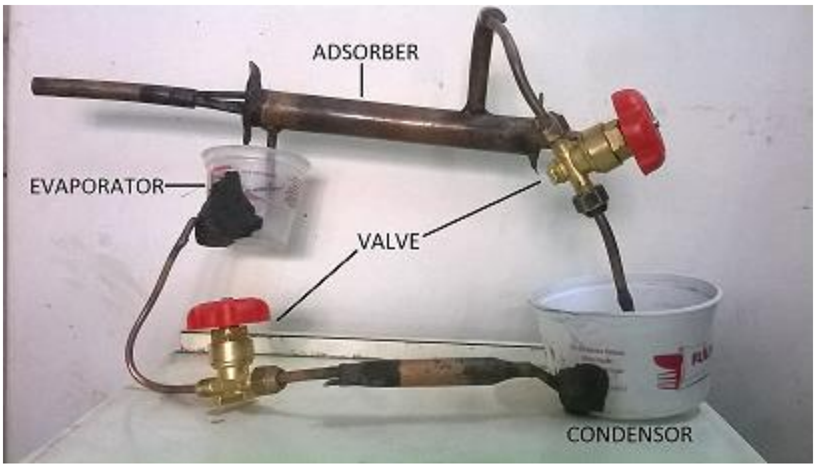


**Figure 1.3 Laboratory scale model of adsorption water chiller**

## 1.4 Methodology of Research

The present research work comprises of three parts, i.e. Adsorption capacity measurement, development of semi-continuous adsorption chiller and choosing the best working environment for the chiller. Adsorption capacity is the ratio of a mass of refrigerant adsorbed per unit mass of adsorbent. In this research work, the adsorption capacity of methanol on Indian ACF (Environ make) has been measured considering the isobaric adsorption. In Isobaric adsorption, the bed temperature decreases stepwise but need to control the water bath temperature, so the refrigerant pressure remains constant. Adsorption experiments were carried out at constant evaporator temperature, and the adsorbent temperature was varied over a range of 15 to 80 ° C.

The ACF-Methanol based semi-continuous adsorption chiller has been designed and developed by considering the input factor as Hot water temperature, Cold water temperature, Condenser water temperature and Frequency (ratio of time of hot water to cold water supply) for getting a response regarding COP and SCP. With the physio sorption phenomenon and requirement of cooling, the design of a system is performed. The overall system is designed and developed for better cooling effect and to identify the best combination of a parameter for efficient performance. To identify best working environment of semi-continuous solar power adsorption water chiller, series of experiments was performed by varying different parameters like hot water temperature, cold water temperature, a flow of water, condenser temperature, time of supply (hot water and cold water) etc. During experiments, drop in temperature of water available in the evaporator is observed as a cooling effect. The important performance parameters SCP and COP are obtained by cooling effect and electric input to the water heater.

## 1.5 Thesis Outlines

Chapter 1 describes ***Introduction*** regarding research work on solar-powered semi-continuous adsorption water chiller. The focus here is on the need of specific research and brief methodology carried out for said research.

Chapter 2, deals with ***Literature*** about adsorption refrigeration system is reviewed. The emphasis here is on adsorption cooling cycle, adsorption capacity and working pairs. Research gap is identified from the survey.

Chapter 3, underlines on the experimental investigation on the ***Adsorption capacity of working pairs*** with isobaric adsorption principle. The outcome of study gives the best working pair for solar powered semi-continuous adsorption water chiller.

Chapter 4, highlights on ***Hybrid adsorption system design*** and development of semi-continuous chiller. The effort here is on scientific design of each component of the system and final development of the system.

Chapter 5, ***Experimental investigation and performance analysis*** are performed in this chapter for selecting best working environment of the system. By providing different combinations of the parameter, the performance of the system is observed.

Chapter 6 emphasizes on ***Results & Discussion*** part of overall design and performance of the system. Here also the attainment of research objectives and limitations of research is discussed.

Chapter 7, the extract of research work is discussed in ***Conclusion***. The important outcomes from this work are presented and suggest the future scope of work.

# CHAPTER 2

# Literature Review

Absorption refrigeration system is widely used for large tonnage capacity, and it has a limitation of having a rectifier, pump, and vibration. For small to large tonnage capacity system, Adsorption proved its capabilities in cooling products as well is powered by low-grade heat either solar energy or waste heat. For the development of adsorption refrigeration system, it has to concentrate on various significant parameters like working pressure, generator temperature and adsorption capacity. Adsorption capacities straight reflect the size of the system as well refrigeration effect. In present review work, more focus is on a hybrid system of water heating system plus a refrigerator and adsorption capacity of activated carbon-based adsorbent. Also performed review on advanced adsorbent based on AC, Continuous/Intermittent system, different AC-refrigerant pair and applications coherent with adsorption capacity and hybrid system.

## 2.1 Adsorption capacity

The performance of Adsorption refrigeration system relies on an appropriate working pair of adsorbent and refrigerant for a specific application. The system COP, SCP and size are decided by adsorption capacity (kg of refrigerant adsorbed per kg of adsorbent, X or $m^3$ of refrigerant adsorbed per kg of adsorbent, W). The higher the value of X or W gives the efficient performance and helps to reduce the overall size of adsorption chiller. The cooling applications, i.e. ice maker, air conditioner or vaccine storage and design parameters decide the working pair for system design. Many researchers have worked on adsorption kinetics and derived correlation between adsorption capacity, temperature & working pressure. The data derived from the experiment can also validate with standard available adsorption capacity Correlation. It is mandatory to prepare testing setup before performing adsorption experiments. There is two methods for measuring adsorption capacity either by isothermal or isobaric. As per condition, one can set up the design of experiments and perform the measurement.

The following studies cover the adsorption capacity of AC based adsorbent with different refrigerant used in adsorption refrigeration system.

Satyapal and Sun [3], experimentally investigated adsorption capacities and heat of adsorption of Coconut shell-based AC & ACF. The experiment was performed on Micromeritics ASAP 2010 instrument by Nitrogen adsorption isotherm at 77 K with a sample mass of 0.25 gm. They found ACF has 55 % higher methanol adsorption capacity. This is due to higher BET area and pore volume of ACF. AC has an ultra-microspore ( < 7 A° ), which cause longer desorption period and more amount of methanol are undesorbed ( 12 % ) compared to ACF ( 5 % ).The adsorption capacity of methanol in AC powder is 24.70 %, while in ACF 38.45 %.Even-Heat of Adsorption in ACF (55.2 kJ/mol) is found higher than AC (52.4 kJ/mol).

Wang et al. [4] experimented to measure adsorption capacity of AC & ACF with methanol. In the experiment, adsorption capacity was measured by the concept of isobaric method, i.e. at constant pressure. Fig.2.1 shows the adsorption capacity measurement apparatus for working pair.

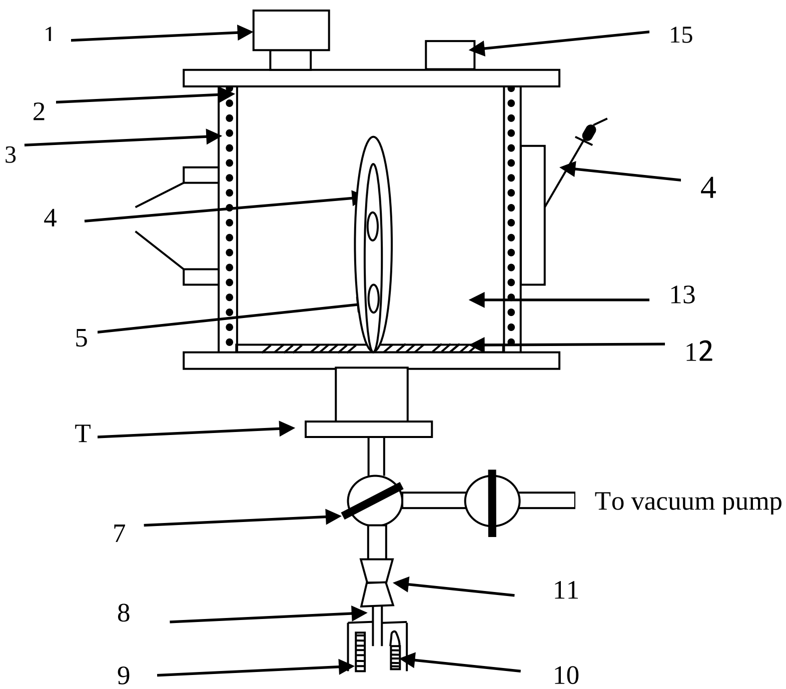


**Figure 2. 1 Measuring apparatus of adsorption capacity[4]**

1- absolute pressure sensor; 2- stainless steel vacuum chamber; 3- electric heater; 4- stainless screen net; 5- Pt-100 temperature sensor; 6- vacuum connector; 7- three way valve; 8- methanol glass tube; 9- millimeter indicator; 10- thermometer ; 11- vacuum connecting tube; 12- stainless steel layer; 13- adsorbent ; 14- temperature control sensor; 15- vacuum feed throughs.

The apparatus consists of stainless steel vacuum chamber as an adsorber bed and glass tube as a methanol level indicator. The temperature of the bed is controlled by the electrical heater with relay and system pressure is maintained initially by a vacuum pump. The adsorber bed and level indicator are connected through a metal tube. To stop the migration of adsorbent, stainless screen net is wrapped over adsorbent, and stainless steel screen layer is kept at the bed bottom from where it is connected to the indicator. By isobaric measurement, it was found that ACF requires less time than AC for methanol adsorption (1/5 to 1/10). They experimented with adsorption temperature of 50°C and 18°C and found that the highest value of x is 0.682 for ACF while 0.284 for AC. They suggested that packing density of bed and flow channels for methanol vapours will play a vital role in adsorption/desorption time.

Wang and Wang [5] suggested improved adsorption model based on modified DR & DA equations for AC/Methanol, ACF/Methanol and Zeolite/Water pair for refrigeration. They evaluated various adsorption equation for working pairs, then suggested modified DA equation for the pairs. They conducted isobaric as well isothermal adsorption experiments for the pair. In the experimental setup, adsorption chamber (180 mm L x 50 mm D), glass tube, temperature sensor, thermostat, pressure sensor and data acquisition system are located as shown in Fig.1.By keeping nearly zero pressure and generation temperature of 120°C for AC and 200°C for Zeolite for 4-6 hours, complete desorption is observed in the system. The experimental analysis comprises the three isobars of AC on methanol at 37.7 mm of Hg. (Tsat-3°C), 55.4 mm of Hg. (Tsat-10°C), 97.3 mm of Hg. (Tsat-20°C), as well three isothermal adsorptions of AC-Methanol at 110°C, 43°C and 13°C. The outcome of the study is compared with three isotherm model of adsorption. It was suggested that improved model equation is best suitable for adsorption characteristics for the pair. The maximum adsorption capacity found for AC-Methanol is 0.294 kg/kg, Zeolite-water is 0.203 kg/kg and ACF-Methanol is 0.602 kg/kg.

El-Sharkawy et al. [6] developed experimental set up for adsorption capacity of activated carbon fibres-ethanol is shown in Fig.2.2. They performed isobaric adsorption experiments at a range of adsorber temperature from 11 to 60°C by with constant evaporator temperature. The experiments revealed that adsorption capacity is proportional to the apparent density of ACF and its value is 0.797 kg/ kg, which is higher due to the large surface area and has a better affinity towards refrigerant. On the same test set up El-Sharkawy et al. [7] investigated comparing the adsorption capacity of methanol on activated charcoal with Maxsorb III for air-conditioning and ice making applications. It was concluded that Maxsorb III has 72 % higher adsorption capacity than activated charcoal due to its better adsorptive properties. It was suggested that D-R equation is best suited to the activated carbon-based adsorbent.

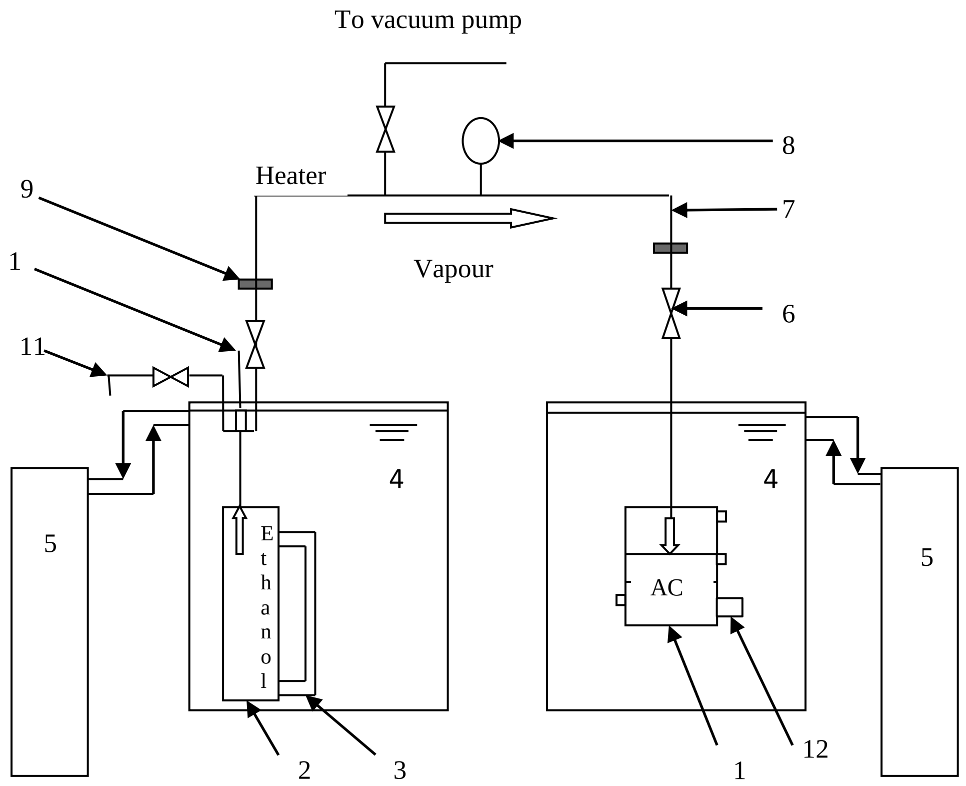


**Figure 2.2 Schematic diagram of experimental set up[6]**

1. Adsorber 2. Evaporator3.glass tube4.constant temperature water bath5.water circulator, 6. Valve 7.connecting tube8.pressure sensor 9. Connecting flange10.thermocouple, 11. Refrigerant injection tube 12.thermocouple inlet

The thermogravimetric analyzer is used to measure the mass uptake of ethanol on ACF by Saha et al. [8]. The Schematic diagram of the TGA experimental apparatus is shown in Fig. 2.3, in which evaporator temperature was kept constant at 15°C and adsorber temperature varied from 27 to 60 °C under isobaric adsorption. The highest uptake of ethanol on ACF is 0.67 kg/kg observed at 27°C after 3600 seconds, and it was concluded that ACF-ethanol is suitable for large capacity adsorption chiller.

The intermittent adsorption refrigeration system with plate fin type heat exchanger was developed by Saha et al. [9] by picking the best working pair. Six adsorbent was used in Nitrogen adsorption isotherm method to evaluate the adsorption capacity for efficient cooling. The ACF (A20) was observed to have highest adsorption capacity (0.797 kg/kg) than all others adsorbent due to the larger surface area (1.9 x $10^6$ $m^2$/kg) and higher total pore volume (10.28 x $10^{-4}$ $m^3$/kg). The Schematic diagram of intermittent ACF/ethanol adsorption refrigeration system is as shown in Fig.2.4. In the experiment, generated adsorption heat during the cyclic process was released by supplying cooling water to adsorber bed. It was concluded from the study that with short cycle time (5 min), higher desorption heat transfer coefficient is attained and the sensible heat transfer losses can be reduced by using a compact heat exchanger for adsorber bed.

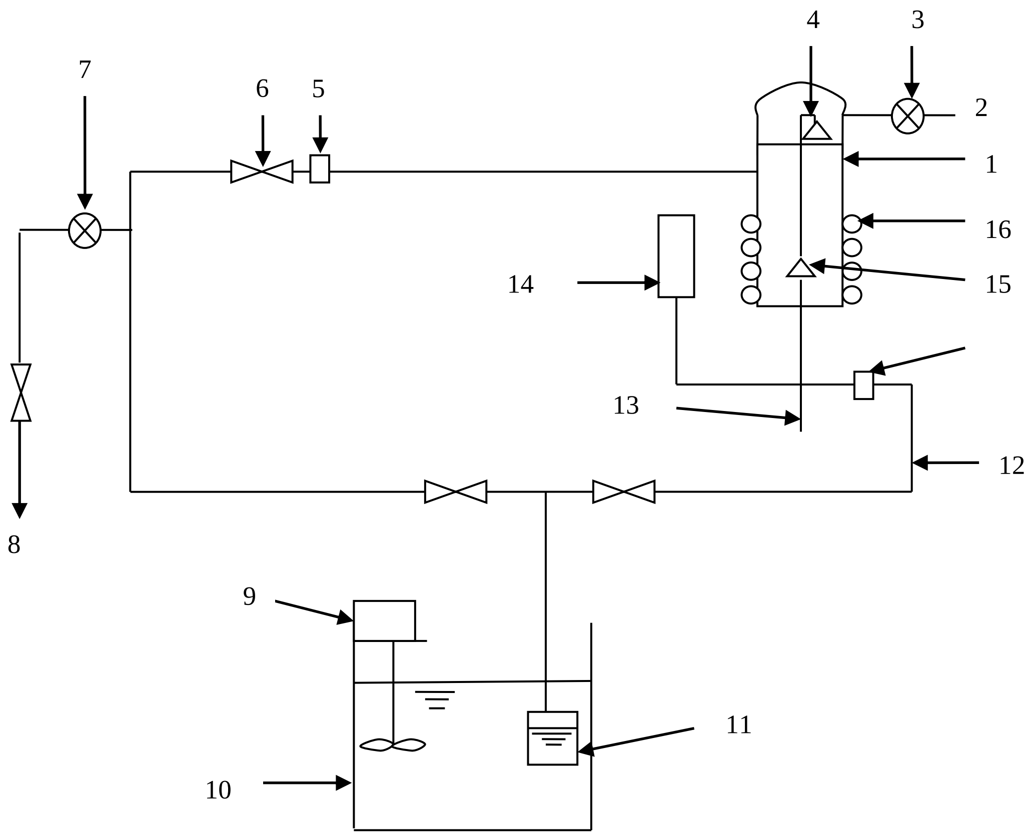


**Figure 2.3 Schematic diagram of the TGA experimental apparatus[8]**

1. Reacting chamber 2. Helium injection port 3. Gas flow regulating valve 4.microblalnce 5. Porous mesh (damper) 6.valve 7.pressure regulating valve 8.vaccum pump connection 9.water circulator 10.water bath 11.evaporator 12. Tape heater 13. Thermocouple 14.pressure sensor 15.sample pan 16 heater

Alghoul et al. [10] carried out an experimental and analytical investigation on Malaysian AC-methanol pair for a hybrid system of the water heater and adsorption ice maker. The schematic diagram of the test rig for testing adsorptive properties (isobars) between activated carbon and methanol is shown in Fig. 2.5. In their investigation, three types of AC (AC-4050, AC-5060 and AC-6070) were selected as an adsorbent with methanol as a refrigerant for dual purpose solar system. It was discovered from the study that AC-5060 gave the best performance in the temperature range of 30 to 110°C, due to a maximum value of adsorption capacity (0.36 ml/g) among the adsorbent used in the system. It is recommended that keep condenser- adsorption temperature below 35°C. Otherwise, the advanced adsorbent material is required for the hybrid system.

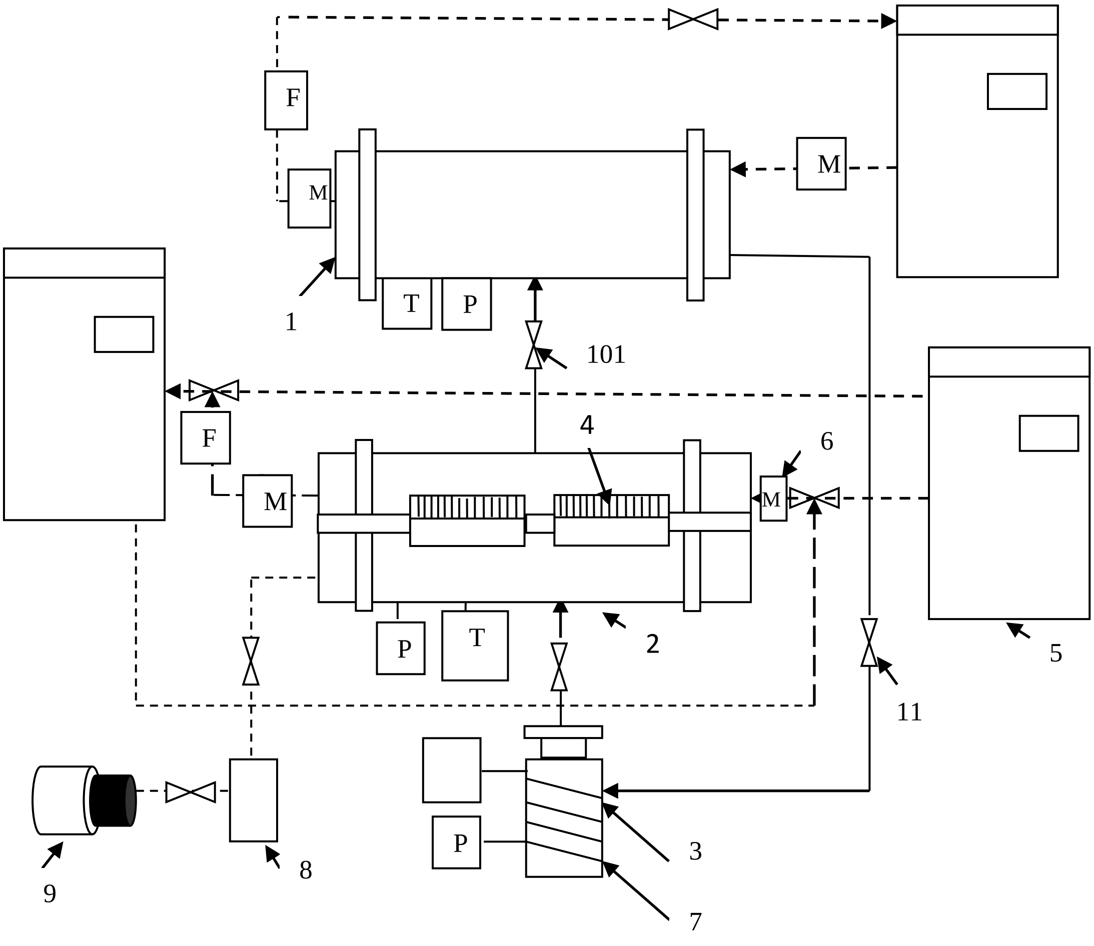


**Figure 2.4 Schematic diagram of intermittent acf/ethanol adsorption refrigeration system[9]**

1. Condenser 2.adsorber 3. Evaporator 4.heat exchanger 5. Heating/ cooling water circulator 6. Mixing chamber 7.belt heater 8.refrigerant tank 9. Vacuum pump 10. Quick shut valve: 11. valve
P – pressure gauge T- thermocouple F- flow meter

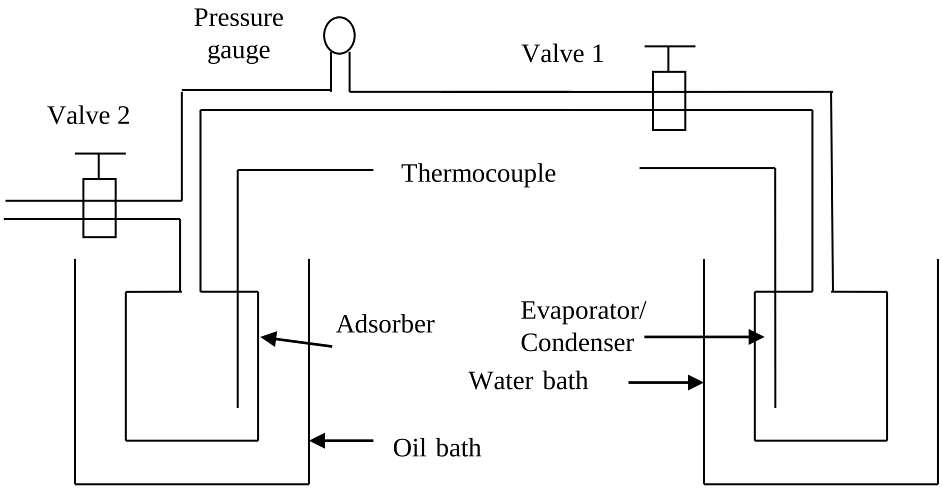


**Figure 2.5 schematic diagram of the test rig for testing adsorptive properties (isobars) between activated carbon and methanol[10]**

The three methods of measuring adsorption capacity were reviewed by Wang et al. [11] in their study on the working pair for refrigeration. They gave a brief explanation on volumetric, liquid level and gravimetric method for measuring the adsorption performance. In volumetric method, the quantity of adsorbed mass is calculated by measuring the variation of either pressure or volume in a vessel which shown in Fig.2.6. The refrigerant level in condenser or evaporator during adsorption process is measured by using liquid sensor and using the density of refrigerant, the mass of adsorbed refrigerant is decided. The test unit for liquid level measuring method is shown in Fig.2.7. In the gravimetric method of adsorption capacity, quartz spring is used as shown in Fig.2.8. The length of quartz spring before and after adoption with reference to the length of quartz spring during empty vessel gives the adsorption capacity of working pair.

Askalany et al. [12] performed an experimental study for analyzing the adsorption-desorption characteristics of granular activated carbon with R134a in a temperature range of 25 to 65°C.  The highest adsorption capacity 1.68 kg/kg is observed at an evaporator temperature of 25°C and after 16 minutes of adsorption operation. The schematic diagram of experimental set up is shown in Fig.2.9.The main difficulties found during experiments was the realization of high working pressure (10 bar), which requires better system design and instruments for the experiments. It was revealed from an experiment that the maximum adsorption capacity is decreased with increase in adsorber temperature.

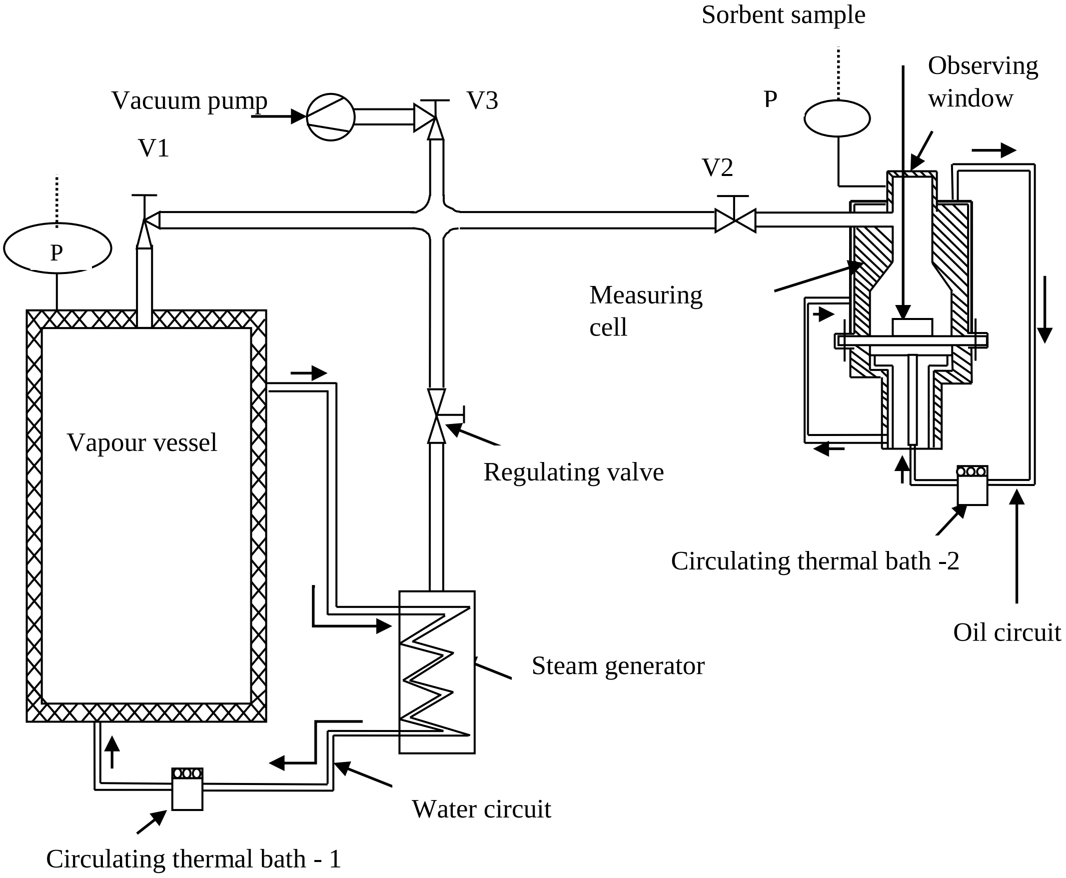


**Figure 2.6 Test-rig for volumetric method[11]**

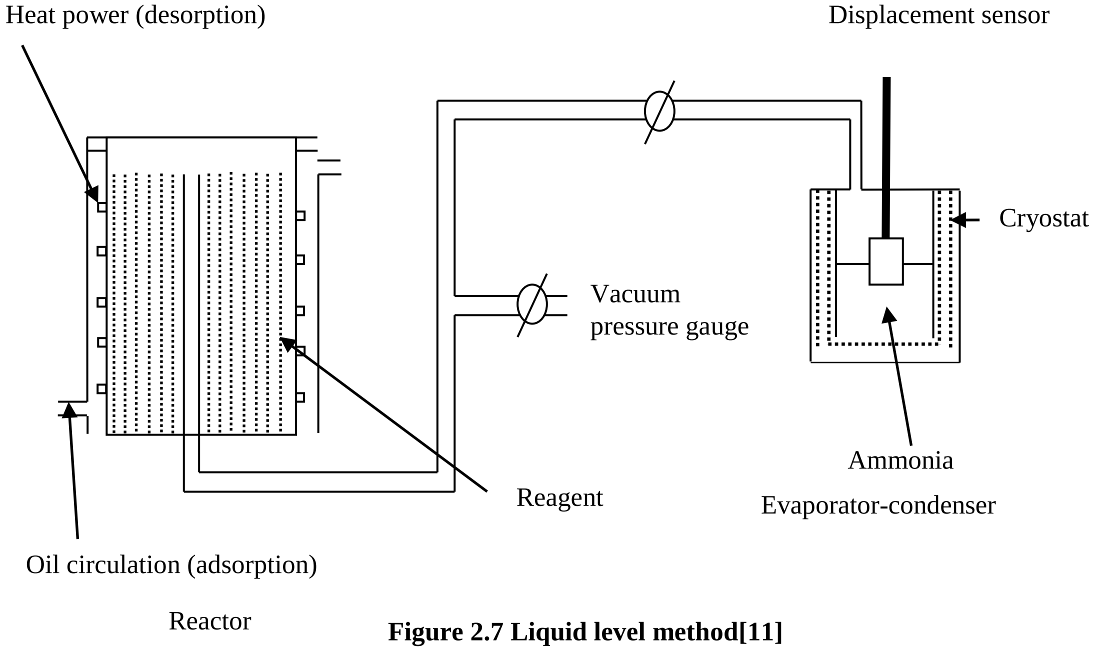


**Figure 2.7 Liquid level method[11]**

The adsorption capacity of R134a on activated carbon and ACF are compared in the experimental investigation of Saha et al. [13] by using RUBOTHERM ISOSORP 2000 equipment. The schematic diagram of experimental set up is shown in Fig.2.10.The highest uptake observed is 1.3 kg/kg for ACF at 30.2°C and 0.94 kg/kg for AC at 26.8°C during isobaric adsorption in the temperature range of 30 to 80°C. In their study, tested data was compared with D-A, Langmuir and Toth model of adsorption isotherm. The experimental results of both working pairs were best suitable for D-A isotherm models. Hence it is concluded that D-A equations with volume corrections can be applied to the activated based adsorbent.

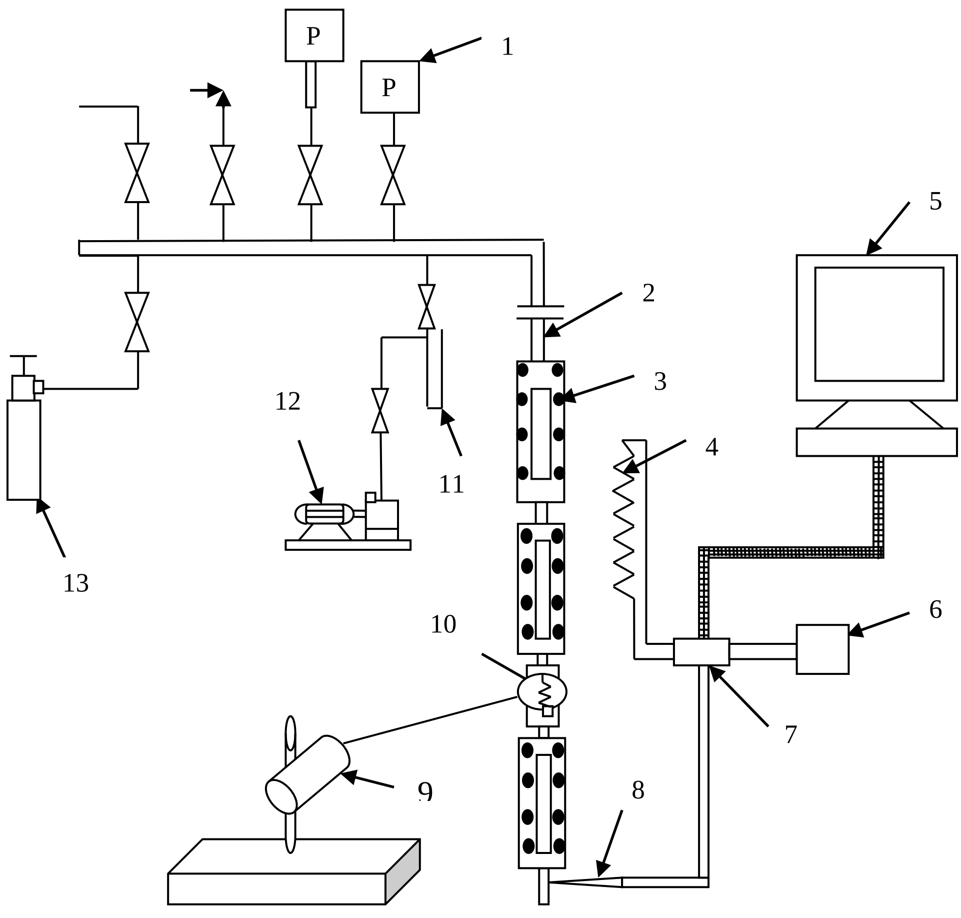


**Figure 2.8 Test unit for gravimetric method[11]**

**1**. Pressure Gauge 2.Measuring Tube, 3.Viewing Glass, 4.Electric Heater, 5.Computer, 6.Electric Source, 7.Temperature Controller, 8.Thermocouple, 9.Altimeter, 10. Quartz Spring, Basket And Adsorbent, 11.U Shape Pressure Gauge, 12. Vacuum Pump, 13.Liquid Nitrogen Cylinder

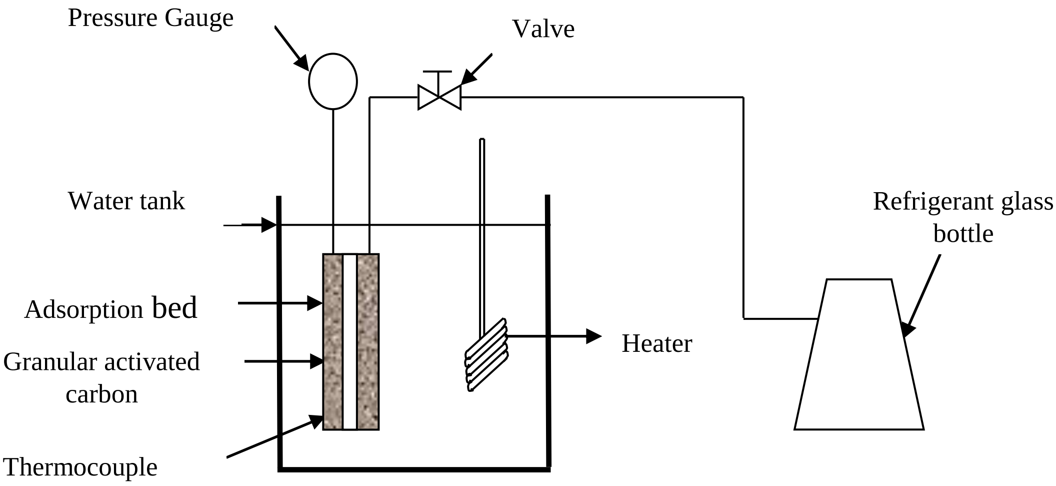


**Figure 2.9 Schematic diagram of the Experimental test rig[12]**

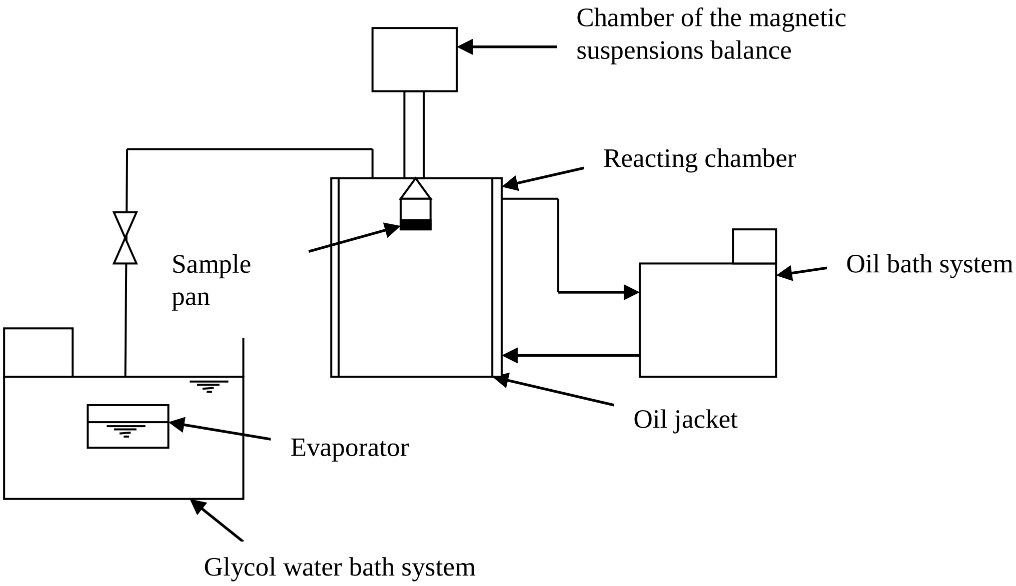


**Figure 2.10 Schematic diagram of the experimental setup[13]**

The test unit for adsorption capacity measurement of water on to composite adsorbent was developed by Tso and Chao [14], which is shown in Fig. 2.11. The composite adsorbent was made of activated carbon, silica gel and calcium chloride in different proportion were used for evaluating the best working pair of energy efficient solar adsorption cooling and dehumidification system. The AC-12 (66% AC+13%Silica gel+21% $CaCl_2$) achieved highest adsorption capacity (0.23 kg/kg) at a system pressure of 0.9 kPa, which was better than raw activated carbon (0.0339 kg/kg) due to having composite properties of adsorbent.

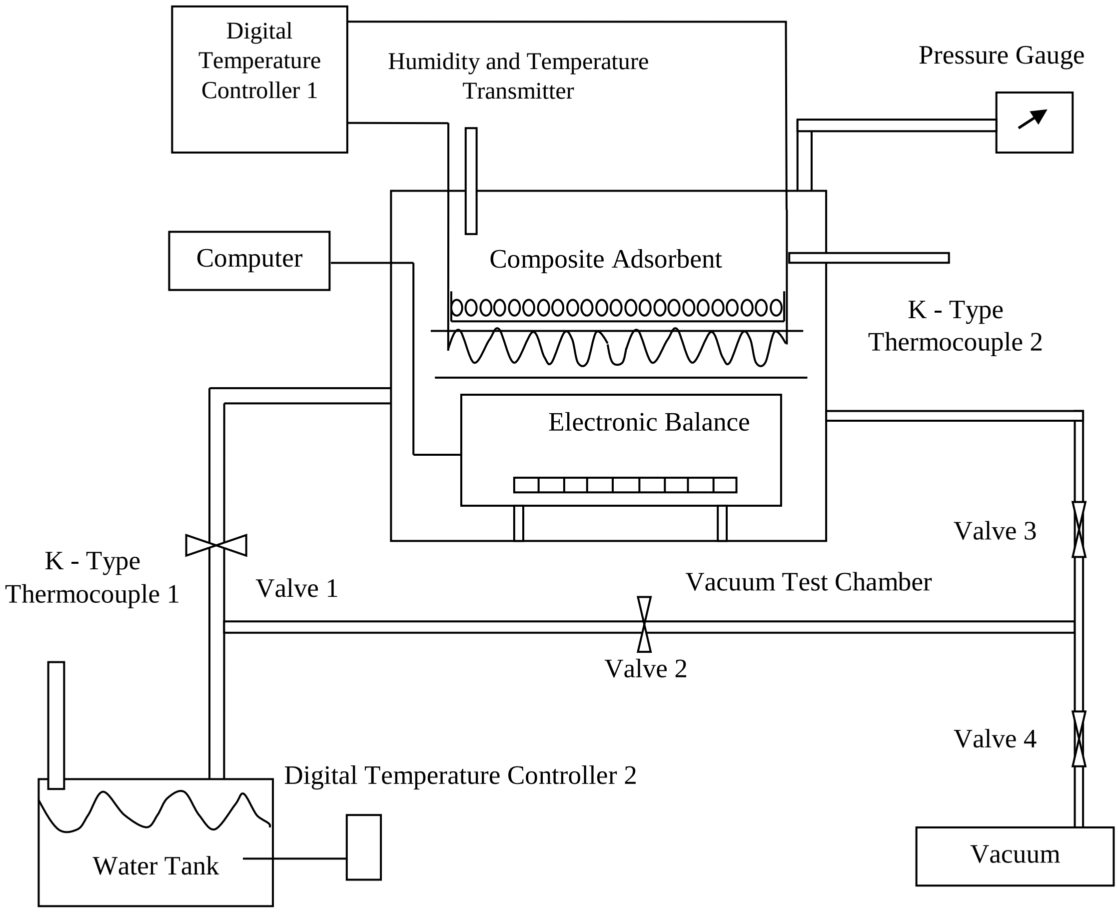


**Figure 2.11 Schematic diagram of the adsorption rate test unit[14]**

Attalla and Sadek [15], experimentally investigated adsorption characteristics of Granular activated carbon GAC / R134a pair in an isothermal way. The Schematic diagram of the experimental setup is shown in Fig. 2.12. They measured instantaneous adsorption capacity at an interval of 60 seconds under constant volume, constant temperature and variable pressure. In the setup, Hot /cold water units used for controls the bed temperature and digital balance used for measurement of R134a mass which is going to adsorb or desorb in the system. By keeping adsorber bed temperature constant, R134a is allowed to adsorb in the bed, which raises the system pressure and digital balance reading gives adsorption capacity. The same experiment was repeated for different bed temperature, i.e. ranges from 20 °C to 60 °C. Also, the effect of pressure on adsorption capacity at a different temperature is examined. The maximum adsorption capacity of this pair is found to be 1.92 kg R134a/ kg GAC 20 °C after 1200 sec. They observed adsorption uptake are reduces with the rise in temperature due to the generation of heat of adsorption. One important conclusion is drawn that better adsorption capacity achieved by finned tube heat exchanger for the bed.

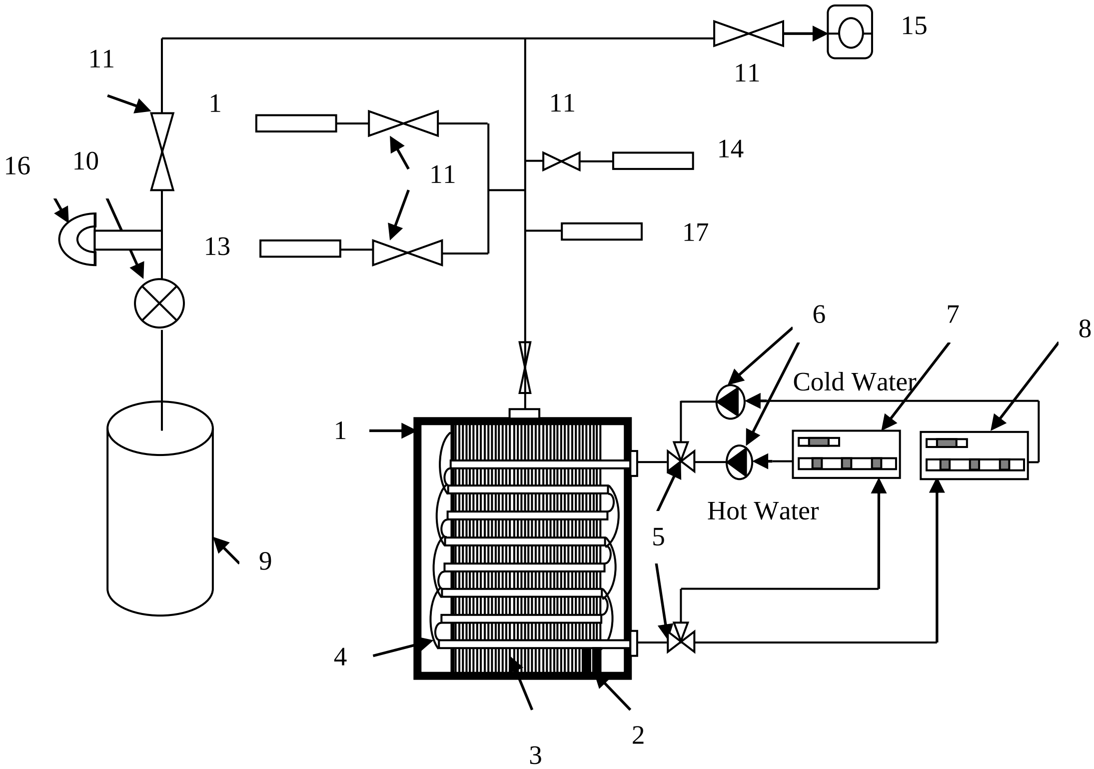


**Figure 2.12 Experimental setup[15]**

1. Vacuum chamber; 2.Adsorbent; 3.Flat Fins; 4.Tube; 5.Theree way valve; 6. Water pump; 7. Hot water unit; 8.Cold water unit; 9.Refrigerate cylinder; 10.Pressure regulator; 11.Valve; 12. Pressure transducer; 13.Vacuum gauge; 14.Mass flow control; 15.Vacuum pump; 16. RTD Temperature Measure; 17.Temperature measuring unit

Ibrahim et al. [16] measured adsorption capacity of three adsorbents namely parent Maxsorb III, KOH-H2 treated Maxsorb III, and a metal-organic framework (MOF) material namely, MIL-101Cr with ethanol in magnetic suspension adsorption measurement unit (MSB-VG-S2), BEL Japan. The Schematic diagram of the experimental setup is shown in Fig. 2.13.For adsorption capacity measurement, they kept adsorption temperature constant and varied evaporator temperature until relative pressure become 0.9. Also performed adsorption uptake experiments for different adsorption temperature (30- 70° C) with relative pressure (0.1 - 0.9).By using Dubinin-Astakhov equation and isothermal adsorption experiment, the adsorption uptake (kg/kg) found was 1.2 for parent Maxsorb III/ethanol, 1 for KOH-H2 treated Maxsorb III/ethanol and 1.1 for MIL-101Cr/ethanol. In their study, except surface area nowhere was mentioned that which parameter affect the adsorption uptake for a different pair.

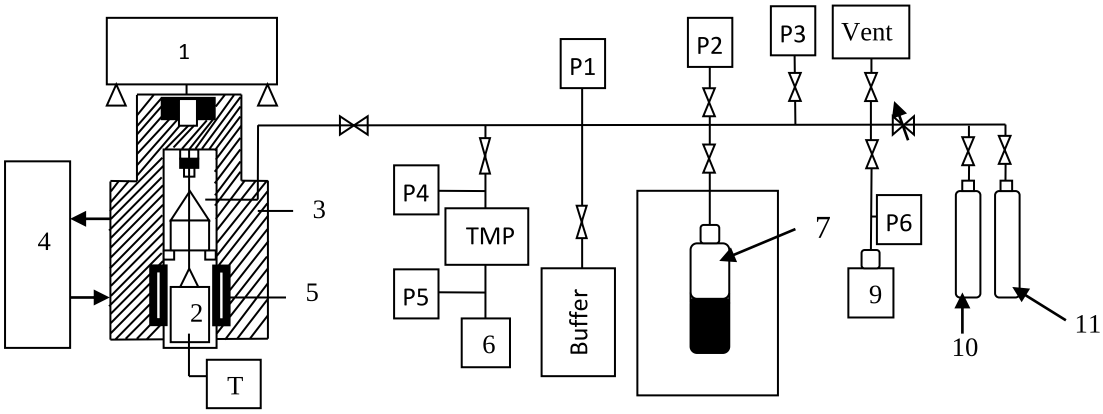


**Figure 2.13 Schematic diagram of experimental setup[16]**
1.Magnetic suspension balance;2.Sample basket;3.Oil jacket;4.Oil bath;5.Sheathed heater;6.Rotary pump;7.Liquid ethanol;8.Isothermal oil bath;9.Diaphragm pump;10.Nitrogen cylinder;11.Helium cylinder;T:Thermocouple;P1-P6:Pressure gauges;TMP:Turbomolecular pump

El-Sharkawy et al. [17] experimented to measure porous properties of composite adsorbent (*Maxsorb III+expanded graphite +binder*) with Nitrogen adsorption technique. Experimental results discovered that consolidated composite adsorbent has a higher adsorption capacity and higher thermal conductivity than the traditional adsorbent. It has been discussed that composite adsorbent produces the better cooling effect. The highest adsorption capacity of composite adsorbent (70 %*Maxsorb III+20% expanded graphite + 10% binder*) -ethanol pair is observed 0.89 kg/kg which is 1.74 times than the Maxsorb III-ethanol pair. The difficulties found during preparation of composite and cost involved were not discussed in their study. It is important to show the limitations of consolidated adsorbent and their lifespan concerning the cooling application, which has been missing in work.

Loh et al. [18]performed the adsorption capacity experiment by using constant-volume−variable pressure (CVVP) approach and examined the data with the Dubinin−Astakhov (DA) equation. Three adsorbent (activated carbons, Maxsorb III & ACF-A20) were selected for isotherm measurement with four refrigerant namely R134a, R290, R410a, and R507a. It is observed that Maxsorb III-R134a pair has highest adsorption capacity (2.22 kg/kg) due to high BET area and large pore volume. It was concluded that the mass uptake varied directly with a density of refrigerant.

Shmroukh et al. [19]carried out review study on working pairs for adsorption chiller. In their study, the classical as well modern working pairs were covered with applications, available generator temperature, environmental concern and adsorbent fitting feature over the heat exchanger. It was concluded from the review, that highest adsorption capacity observed in Maxsorb III-R134a pair in cooling applications. This pair produces very high system pressure which impels better design of system components. The GWP of Maxsorb III-R134a pair is found to be 1300, is higher than a natural working pair for environmental concern. This review study helps to select the best working pair and gave comparisons for major existing pairs. The ACF-Methanol pair has a potential for solar-powered adsorption water chiller with a small available source of energy.

Experimental analysis on adsorption isotherms of Maxsorb III/HFC-152a is investigated by Ghazy et al. [20] in the temperature range of 25 to 75°C. It is observed that adsorption capacity decreases with increase in adsorber temperature due to the release of heat of adsorption. Additionally, the larger cycle time depreciates the adsorption uptake of HFC-152a on Maxsorb III. The highest adsorption capacity is observed 1.3 kg/kg after 570 seconds of the process and at a temperature of 25 °C.

Brancato et al. [21]performed an experimental study on adsorption dynamic with activated carbon-ethanol pair for ice making and air conditioning application. In their study, volumetric large temperature jump (V-LTJ) and gravimetric large temperature jump (G-LTJ) method were used for various configuration of adsorbent, i.e. activated carbon on flat metal plate exchanger, aluminium finned flat tube exchanger. It was discovered from a study that adsorbent having a higher surface to mass ratio gives the maximum adsorption capacity, not the grain size of adsorbent. The flat adsorbent bed offered poor performance due to extra resistance of interparticle heat and mass transfer through the fins. The highest adsorption capacity was found to be 0.39 kg/kg in a heat exchanger configuration with larger surface to mass ratio and 0.43-0.60 mm grain size. Hence it was concluded that choose adsorbent which having higher surface area per unit mass for adsorption chiller.

The adsorption uptake of ethanol on to waste palm trunk and mangrove based activated carbon was experimentally measured by Pal et al. [22], within a temperature range of 30 to 70°C in magnetic suspension unit. The realized adsorption capacity at 5°C evaporator temperature, for mangrove based activated carbon, was 1.65 kg/kg and for waste, palm trunk based activated carbon was 1.90 kg/kg at a desorption temperature of 85°C and a condenser temperature of 30°C. The experimental data was found best suitable for D-A and Toth isotherm model.

It is discovered from the literature review that an adsorbent having larger surface area and higher total pore volume performs, best in adsorption chiller. The adsorption capacity of working pair decides the performance of the system. The traditional adsorbent material performs better below 35°C adsorption and condenser temperature; else it is required to use composite adsorbent, which ultimately adds cost and complexity to the chiller. ACF provides larger surface area and ease in packing which makes it favourable for adsorber bed.Methanol as a refrigerant gives better performance due to its high vapour pressure, low boiling point and high latent heat .

From the literature survey on adsorption capacity, ACF- methanol was elected as an adsorbent-adsorbate pair for a proposed water chiller. The packing density of ACF in adsorber bed is accepted more than 100 kg/m$^3$ for better adsorption during the cooling process. The conventional solar water heater operated by FPC, ETC can generate hot water in the range of 40 to 70° C. It is encouraged to select the working pair, which is working in this temperature range. The review suggested that methanol as a refrigerant accomplish effective refrigeration with ACF in adsorption chiller. The adsorption capacity of ACF-methanol pair can be effectively measured in isobaric adsorption method in which keeping the evaporator temperature constant and measure adsorbed mass methanol by changing adsorber temperature. The isobaric adsorption capacity measurement technique is a help to select the best working pair for desired cooling effect in adsorption chiller. The density of methanol is marginally higher than ethanol and boiling point is lower than ethanol, which helps for better adsorption/desorption during the process with available lower generation temperature. It was also accomplished that Dubinin-Astakhov (D-A) model for adsorption isotherm is best suitable for ACF-Methanol pair.

## 2.2 Intermittent cycle

Intermittent adsorption chiller has 24 hours of cycle time and in a continuous cycle, has 5 to 30 minutes cycle time for cooling. The state of art of this works is mentioned in Table 1.

**Table 2.1 Review table on Intermittent cycle**

| **Parameter/ Author** | ***Boubakri [50]*** | ***González et.al.[51]*** | ***Hassan [54]*** | ***Pons and Guille minot [52]*** | ***Suleiman et.al.[53]*** | ***Wang et.al. [25]*** | ***Anyanwu and Ogueke [40]*** |
|---|---|---|---|---|---|---|---|
| ***Product Load*** | 5.2 kg of Ice/day | 2.2 MJ/ sqm. Per day | 12.15 MJ per cycle | 30kg of Ice/day | 4814.83 KJ | 10kg of Ice/day | 3 kg of Ice/day |
| ***Cooling Effect ( KJ)*** | 2392 | 2200 | 12150 | 13800 | 4814.83 | 4600 | 1380 |
| ***Cooling Effect ( W)*** | 27.68 | 25.46 | 143.75 | 159.72 | 55.73 | 53.24 | 15.97 |
| ***Generation Temp.(° C)*** | 95 | 120 | 120 | 100-110 | 80 | 98 | 100 |
| ***Adsorption Temp. (° C)*** | 22 | 18 | 30 | 25 | 25 | 20 | 20 |
| ***Cycle Time ( hour)*** | 24 | 24 | 24 | 24 | - | 24 | 20 |
| ***Condenser Temp. (° C)*** | 20 | - | 35 | 25-40 | 25 | 30 | 35 |
| ***Evaporator Temp. (° C)*** | -10 | 0.7 | -5 | -3 | 0 | -2 | -10 |
| ***COP*** | 0.14 | 0.086 | 0.616 | 0.12 | 0.608 | 0.067 | 0.015 |
| ***SCP ( W/kg)*** | 1.384 | 3.53 | 3.19 | 1.22 | 2.13 | 1.9 | 1.9 |
| ***Mass of AC (kg)*** | 20 | 7.2 | 45 | 130 | 26.07 | 28 | 8.4 |
| ***Mass of Methanol (kg)*** | - | 2.2 | 10.79 | - | 8.1 | 8 | - |
| ***Collector*** | FPC – 1 sqm. | CPC -0.55 Aperture Area | - | FPC – 6 sqm | FPC – 2 sqm | Heat pipe ETC – 2 sqm | FPC – 1.2 sqm |

From above review table, it has been observed that the overall cycle time is in terms of hours (20-24 hours), Generator temperature ranges between 80- 120 °C, the mass of adsorbent is from few kgs to hundred's kg and a poor value of SCP. These parameters, i.e. large cycle time, higher generator temperature, a large mass of adsorbent and poor SCP restrict the performance of the system. Hence it is proposed to develop adsorption chiller which has less cycle time, moderate generation temperature and low mass of adsorbent with high SCP.

## 2.3 Hybrid System

Rivera et al. [23] developed prototype solar intermittent refrigeration system for improving the living condition of Mexico people. The objective of their study was to develop a novel low cost solar intermittent adsorption refrigeration system for ice production with no moving parts and negligible maintenance, suitable to be operated in rural communities where electricity supply is not available. The system was designed for SCP of 8 kg ice/day with NH3- Lithium nitrate pair. The system is made of compound parabolic collector, Condenser, Evaporator and Expansion device. Heating and Desorption occurred during the day, and Absorption and cooling happened in the night. This system produced 11 ºC temperature of the evaporator and solar COP 0.08.The system is suggested for ice production where electricity supply is not available.

Luo et al. [24] designed and constructed a solar-powered adsorption chiller. In this study, the parametric analysis performed and concluded for a better combination of the parameter. The refrigeration system consists of water heater, Si-$H_2O$ based refrigerator, cooling tower and fan coil unit. Hot water as a heat source for chiller and cooling tower maintains the low temperature of condenser and adsorber bed. The cooling production is transferred to an air conditioning space through a fan coil unit. The schematic diagram of the solar-powered adsorption chiller is shown in Fig. 2.14. They concluded that the optimum heat recovery time is determined by cooling water flow rate. It was observed that water flow rate at 0.0014 $m^3$/s gave the optimum heat recovery time of 40 s. From the study of solar-powered adsorption chiller, the suitable mass recovery time is about 60–180 s, the suitable time of heat recovery is about 720–900 s, the reasonable hot water inlet temperature is about 65–85 ºC was found. They suggested that for better cooling power and COP, it is advisable to raise the chilled water inlet temperature in the system. The solar-powered adsorption chiller recorded a cooling power about 66–90 W per $m^2$ collector area with solar insolation of 16–21 MJ/$m^2$ with optimum operating parameters. The daily solar cooling COP is about 0.1–0.13 is observed during the study.

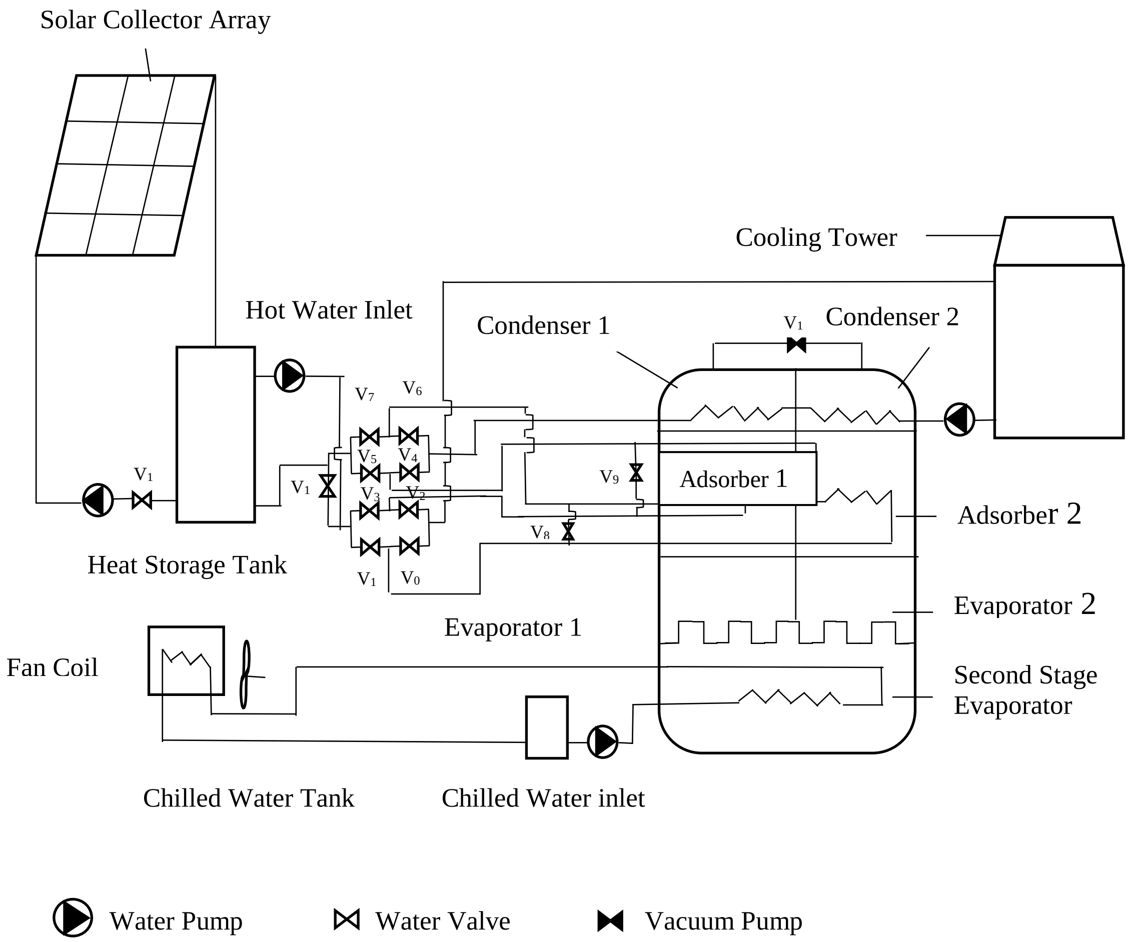


**Figure 2.14 Schematic diagram of the solar-powered adsorption chiller[24]**

Wang et al. [25] developed a hybrid system of the water heater and ice maker which is powered by solar energy. This system consists of the water tank, solar collector adsorber, evaporator, condenser, receiver and valve**.** In the morning, water is heated by solar energy, which raises the temperature of adsorber placed in the water tank. The temperature of adsorbent reaches up to water temperature is only in ideal case. The rise in temperature of adsorbent increases the vapour pressure of desorbed refrigerant up to condensing pressure and desorbed refrigerant vapour condensed in a condenser. The refrigerant collects in the receiver and flows through valve towards evaporator. During the day, the temperature of water continuously increases up to 100º C, which drains out during the evening and used for household application, and refills the water tank by fresh tap water so continuous refrigeration process may occur. This system is produced 30 kg hot water at 47.8ºC, with mean COP $_{heating}$ of 0.34 and in the night, the cooling capacity observed is 0.26 MJ/kg of adsorbent and 1.3 MJ/m$^3$ of heat collecting area.

Tang and Qi [26] developed the solar-powered hybrid adsorption system of the water heater and ice maker, to meet the domestic necessities throughout the year. The schematic of the hybrid system is shown in Fig. 2.15. In the proposed system, the heating of vacuum type collector starts since morning, which in turn will heat the water. As the temperature of water in the collector attains temperature higher than storage tank by 5 to 7 $^oC$, the pump starts its work in terms of circulating cold water from tank to the collector, warm water from collector to adsorber and then return to the storage tank. The warm water heats the adsorber bed and subsequently, the temperature of adsorbent increases which creates desorption process in the developed system. In the night the adsorber bed is cooled by natural convection with ambient air. Hence pressure in the adsorber drops below the evaporation pressure resulting in evaporation which produces ice in the box. The cooling effect remains for the whole night till the next morning. In the system, Adsorber is separated from a collector which allows the use of high-efficiency glass vacuum tube for solar energy collection. Adsorber is also separated from the water tank. Thus the refrigeration quantity is not influenced by the consumption of hot water.

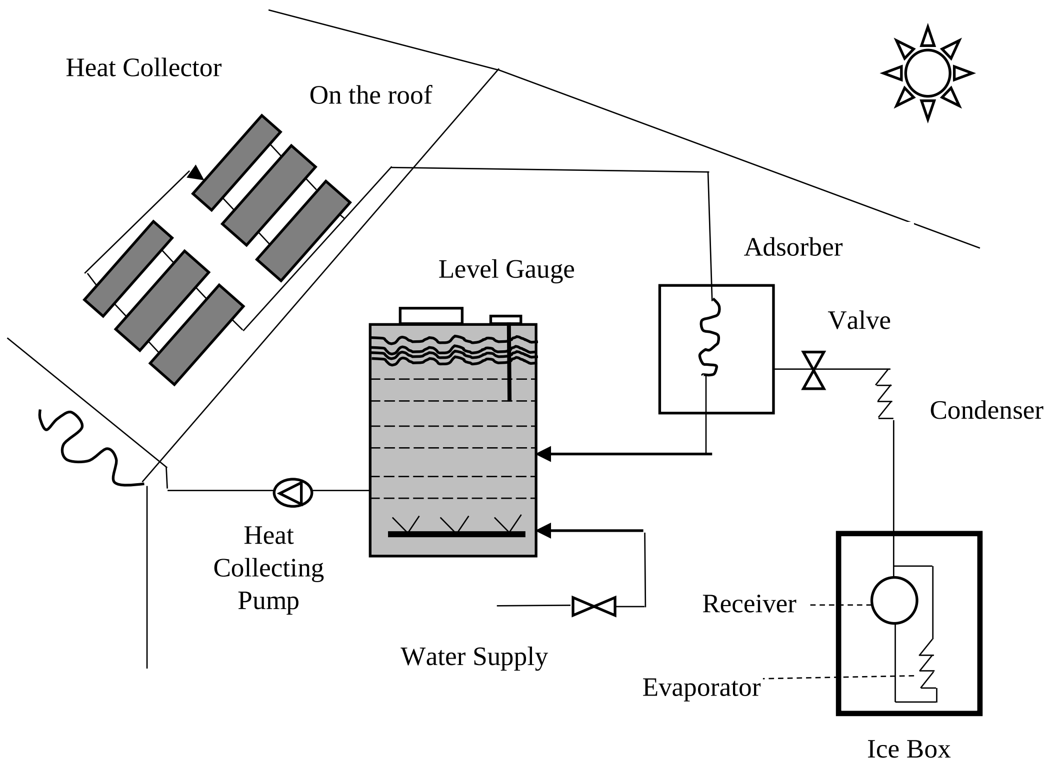


**Figure 2.15 Schematic of hybrid solar powered water heater and ice maker[26]**

The highest observed system COP is 0.069 with $SrCl_2$-ammonia pair and at 93 $^oC$

generator temperature. It was concluded that thermal conductivity of adsorbent material plays a vital role in the better performance of the system. The proposed hybrid system gave two useful output by solar energy which is more efficient than the single system of heating & cooling.

Alghoul et al.[27] carried out parametric analysis for better performance of dual-purpose adsorption system, by using visual basic software with quantitative study approach. The proposed continuous system consists of two adsorber bed, two condensers, two water tank, evaporator, receiver and ice box. In the parametric analysis, the effect of hot water temperature, second adsorber temperature, adsorption - condensation temperature, the mass of ice and adsorbate (activated carbon) on the performance of the system were discovered. It has also been emphasized on the economy with the efficiency of the dual system. The gained maximum value of COP is 0.101 at a temperature of 95 $^{o}$C to maintain an evaporator temperature of –5$^{o}$C with Malaysian *AC* – 5060-methanol pair. It was concluded that adsorption properties of working pair, generator temperature and city water temperature are the important parameters for efficient working of the system.

Thumautok et al. [28] developed dual purpose adsorption system of the water heater and cooling application in Thailand. The system consists of a co-axial tube in tube adsorber, evaporator, condenser and flat plate solar collector. In their study, activated carbon-methanol is used in the proposed system. The gained highest value of COP for heating is 0.11 in solar powered adsorption system. It was concluded from experimental work that hybrid system can satisfy the heating and cooling requirement by solar energy.

Alghoul et al. [29] reviewed multipurpose solar adsorption system used for cooling and water heating. In their study, the review focus on dual purpose-refrigerator and water heater system with the intermittent & continuous operation. Also took care of explaining working pair with the application of this system. It was concluded from the study that solar-powered hybrid system is the best substitute for the conventional water heater and cooling system. The limitations of the dual-purpose system were mentioned in term of poor in performance, large in size and overall expensive in nature.

Sumathy [30] developed AC-methanol based hybrid system to resolve the problems of adsorption system, uneven cycle time and low SCP of the refrigeration system. The schematic of the system is shown in Fig. 2.16. In the proposed design, the adsorber bed is kept inside hot water tank to conserve sensible and latent heat during the process as well reduces the chance of methanol disintegration at high temperature. The overall SCP found in the proposed hybrid system is 5 kg ice /day using 0.92 $m^2$ solar collector. It was suggested from a study that advances material like ACF will improve the performance of the system.

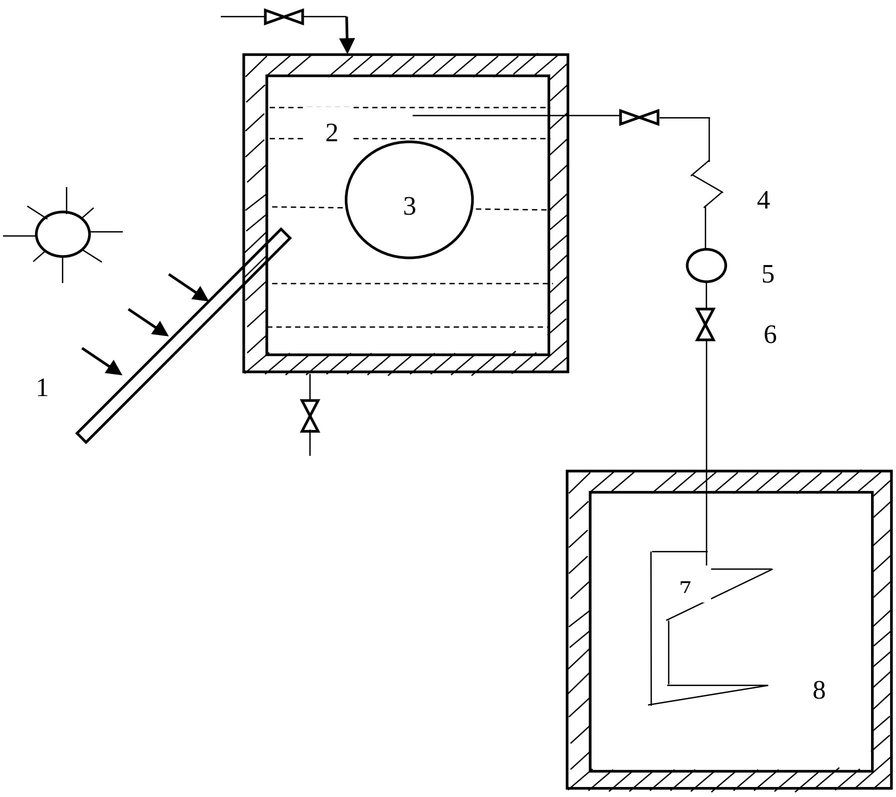


**Figure 2.16 Schematic of hybrid System[30]**, 1. Solar collector; 2. Water tank; 3. Adsorber; 4. Condenser ;5. Receiver ; 6. Valve ; 7. Evaporator ;8. Refrigerator

Popa et al. [31] proposed an innovative design for a solar-powered hybrid system which can operate throughout the day. The hybrid system consists of two adsorber bed in the upper and bottom side of collector separated by adiabatic layer and enclosed by glass cover with revolving mechanism. The theoretical analysis was carried out on continuous adsorption cycle to simulating the real-life situation. The relation between cooling/heating coefficient with solar time and water mass available water tank is identified for better performance. The proposed system gave a maximum COP of heating as 0.5, maximum COP of cooling as 0.25, maximum SCPa as 30 W/kg and maximum SCPc as 140 W/kg for 50 kg of water in the study. In their study, performance also checked with 10 kg and 30kg mass of water. It was not an experimental study. Hence difficulties found for revolving bed and effect of the environment were not discussed.

Alghoul et al. [32] suggested the novel design of a dual purpose solar continuous adsorption system for domestic refrigerator and water heating. In the investigation, Malaysian AC and methanol are used as a working pair for the system. The proposed system consists of two adsorber beds, two condensers, receiver, evaporator and ice box. The calculated $(COP)_{dual\ system\ -ice}$ as 0.091, $(COP)_{cycle-ice}$ as 0.44, $(COP.)_{dual\ system\ –domestic\ hot\ water}$ as 0.73 and $(COP)_{dual\ system}$ as 0.821 in theoretical study. The cost analysis and payback calculation were also performed for this system. The limitations of proposed design were not included in the research work.

Baiju and Muraleedharan [33] performed an experimental investigation of dual solar adsorption refrigeration system with AC-methanol pair at National Institute of Technology, Calicut, Kerala, India. The system consists of a parabolic solar collector, two water tanks, two adsorbent beds, condensers, an expansion device, evaporator and accumulator. The achieved mean cycle COP. is 0.196 during daytime and 0.335 during night time. Also reported mean SCP, during daytime and nighttime were 47.83 and 68.2. They concluded that their system would perform sound at night time compared to daytime. The proposed system was given maximum performance at a generator temperature of 72.4 ºC. It was concluded from the experimental study; two-stage adsorption system performs well with parabolic concentrator type collector and AC-methanol pair.

Tso et al. [34 ]used a simulation model to find the effect of various parameters on the performance of composite adsorbent base double adsorber chiller. In their study, SCP and COP were directly affected by hot water temperature, cold water temperature and mass flow rate of water. It was explored that composite adsorbent (sodium silicate + AC +calcium chloride)-water based chiller generates higher COP, SCP and cooling effect than traditional adsorbent, i.e. silica gel-water, AC-water, due to its better adsorptive properties. The maximum SCP (380 W/kg) and COP (0.65) was observed at a generator temperature of 85 ºC and evaporator temperature of 14 º C in double bed adsorption chiller. In their conclusion, it was suggested that efficient adsorption chiller could be achieved by the composite adsorbent. The limitations and life of composite adsorbent were not discussed in the study.

The solar-driven continuous AC-methanol based adsorption cooling system was developed by Hassan et al. [35] by using double adsorber bed. In their study thermodynamic analysis of system component and effect of the various parameter on system performance were discussed. The isothermal adsorption principle and computer program are used for simulating the working environment. The observed outcome of the study was higher COP (0.6), better cooling effect (9.137 MJ/day), efficient heating effect (24.16 MJ) with total ice production of 20.16 kg. It was concluded that proposed system could operate for 24 hours for cooling and air conditioning applications.

Berdja et al. [36] developed intermittent adsorption tube collector type refrigeration system for the climate of Algeria. The excel program was incorporated into the mass of working pair, the design of system components and performance estimation. In their prototype, 1.06 $m^2$ solar collector, 10.6 kg activated carbon, and 2.86 kg methanol were employed for the 100-litre volume of the refrigerator to achieve COP of 0.49. The heat loss from refrigerator section during the night was simulated by ANSYS-Fluent tool for phase change phenomenon of ice. It revealed from work that solar powered intermittent adsorption chiller could satisfy the miniature requirement of cooling.

The compact size one-bed intermittent adsorption cooling system was developed by Miyazaki et al. [37] for refrigeration and air conditioning applications. The proposed system was operated with a various combination of the cycle time of pre-heating, desorption, pre-cooling and adsorption to get flexibility in control of water supply. The adsorption properties of AC-ethanol pair were measured by lumped parameter model, and parametric analysis was performed by global optimization method for efficient performance. The obtained COP was 0.48 and SCP was 140 W/kg at a temperature of 80 ºC with an evaporator temperature of 14 ºC. It was concluded that single bed adsorber cooling system provides better control over cycle time and helps to reduce overall loss from the system.

Mahesh [38] suggested that for lower generation temperature, flat plate collector is the best collector and activated carbon-methanol pair is a best suitable pair for adsorption cooling in a small tonnage capacity. He reviewed various collector and adsorption materials to select best combinations as per applications and available resources for adsorption refrigeration.

**Table 2.2 Summary of Literature Review**

| | **Wang et.al. [25]** | **Tang and Qi [26]** | **Thumautok et.al. [28]** | **Alghoul et.al. [29]** | **Sumathy [30]** | **Popa [31]** | **Alghoul et.al. [32]** | **Baiju and Muraleedharan[33]** | **Leite et.al. [55]** | **Oliveira et.al. [56]** |
|---|---|---|---|---|---|---|---|---|---|---|
| Collector type & area ( $m^2$) | Vacuum Tube – 2 | Vacuum Tube – 4.2 | Flat plate– | Flat plate– 3.60 | Flat plate– 0.92 | Flat plate– 1 | Flat plate– 3.60 | Parabolic concentrator – 3 | Flat plate– 1 | Vacuum tube – 1 |
| Adsorbent-adsorbate Pair | AC-Methanol | $SrCL_2$-$NH_3$ | AC-Methanol | AC-Methanol | AC-Methanol | - | AC-Methanol | AC-Methanol | AC-Methanol | AC-Methanol |
| Cycle | Intermittent | Intermittent | Intermittent | Continuous | Intermittent | Continuous | Continuous | Continuous | Intermittent | Continuous |
| Water mass & Temp | 150 kg -98 ° C | 180 kg -93 ° C | 95 ° C | 116 kg -98 ° C | 80 ° C | 30 kg - 90 ° C | 116 kg -98 ° C | 50 lit -90 ° C | 94 ° C | 75 ° C |
| Mass of Ice/day | 10.5 kg | 11.6 kg | - | 12 kg | 5 kg | SCP 20 W/kg | 12 kg | SCP 68.2 W/s-kg | 6 kg | 7 kg |
| $(C.O.P)_{CYCLE}$ (Refrigeration) | 0.386 | 0.21 | - | 0.413 | 0.12 | 0.2 | 0.440 | 0.334 | - | 0.12 |
| $(C.O.P)_{Solar}$ ( Dual ) | 0.067 | 0.069 | 0.082 | 0.815 | - | - | 0.82 | - | 0.085 | - |
| $(\eta)_{Solar}$ (Water heating) | 0.906 | 0.67 | - | 0.73 | - | - | 0.73 | - | 0.64 | 0.36 |

## 2.4 Outcome from review

- Work on Intermittent / Continuous cycle principle of operation
- System size is directly associated with cooling requirement
- Operated by low to high generator temperature ( 40- 120 °C)
- Flexibility in design of system as per availability of materials and resource
- Robust technology with no risk of crystallization, no danger of damage due to temperatures.
- Working pairs are environmentally friendly

- Very low intrinsic electricity consumption due to the absence of pump. Electricity is only required for the switching valves and the control unit.
- Very little moving parts with the potential of low maintenance effort and costs.
- The high potential of cost reduction in series production due to a few individual parts.
- High requirements to the vacuum tightness of the container with methanol.
- Cyclic temperature variation in the hydraulic circuits requires careful design of the external hydraulic circuits.

**Benefits**

- Energy saving using solar energy
- Environmental Friendly: based on natural refrigerants: H2O, NH3, Methanol, Ethanol
- Low maintenance cost, Absence of Vibration
- Simple to fabricate and operate the water chiller for food/vaccine preservation

**Drawback**

- Low COP & SCP
- high thermal mass
- the poor thermal conductivity of the adsorbent
- larger cycle time

**Conclusion**

This review is written to give an up-to-date work on adsorption capacity and hybrid system of solar adsorption systems. The main conclusions deduced from the present study are:

1. In a conventional refrigeration system, input as electricity or fuel, which add cost to the system. Also, it creates noise and pollution. Solar assisted hybrid adsorption chiller saves electricity and fuel without any pollution.
2. Major problems associated with adsorption technology are low C.O.P., Low SCP and poor heat & mass transfer performance.
3. The idea of Solar assisted hybrid technology of water heater and refrigerator, is limited up to laboratory, i.e. research purpose only. A small number of manufacturers tried to build adsorption system but didn't get large success.

4. This is an alternative solution for electricity shortage areas (Rural Area) which helps in preserving foods and medicine.
5. The size of chiller can be optimized by selecting a proper working pair.
6. By using composite adsorbents, heat & mass transfer performance of the system can be improved.
7. ACF-methanol based adsorption chiller gives the best performance at low generator temperature.
8. The dual-purpose adsorption system is very useful for small to large scale applications.

# CHAPTER 3

# Adsorption Capacity of Working Pairs

The size and performance of Adsorption refrigeration system depend on the application, generator temperature and adsorption capacity of working pair. For specified application and available heat source temperature, one can effective utilizes the adsorption capacity for sizing and better performance of the system. Adsorption capacity is the ratio of the mass of refrigerant adsorbed per unit mass of adsorbent. The cooling effect is produced in adsorption refrigeration system by adsorption and desorption phenomenon taking place at the adsorber bed. The adsorption of refrigerant on adsorbent by providing low-temperature exposure (ambient air, tap water etc.) and desorption by high-temperature adsorption (solar energy, waste heat etc.). The cooling capacity of adsorption chiller is decided by the quantity of refrigerant adsorbed on the adsorbent. The quantity (kg or $m^3$) of refrigerant adsorbed per unit mass (kg) of solid adsorbent is defined as adsorption capacity of working pair. The mass of adsorbent for desired cooling effect is calculated by adsorption capacity. The size of adsorption chiller is governed by adsorption capacity, i.e. higher adsorption capacity provides a smaller mass of adsorbent for desire cooling. Hence the size of adsorption refrigeration system is reduced by using higher adsorption capacity working pair.

One of the important parameter involved in the present investigation is to determine the adsorption capacity of working pair in the adsorption water chiller. Activated carbon fiber-methanol, activated carbon fiber-ethanol and activated carbon pallet-ethanol are used as an adsorbent-adsorbate pair in this study. The experiment is conducted using a stainless steel adsorber, 110 mm diameter by 150 mm height, filled with adsorbent and transparent plastic evaporator, 100 ml capacity, filled with adsorbate. The experiment is performed by isobaric adsorption in the temperature range of 10-100º C at the evaporator temperature of 20°C (water chiller). Experimental investigation showed that Activated carbon fiber- methanol pair has highest adsorption capacity (0.44 kg/kg) compared to activated carbon fiber- ethanol and activated carbon pallet- ethanol pair. The finding revealed that uniform structure and large surface area of adsorbent as well low boiling point and large latent heat of adsorbate had significant effects on adsorption capacity. The effect of time and adsorber temperature on adsorption capacity is also discussed in this study.

## 3.1 Introduction

Over the last five decades, researchers have made a significant investigation of the solar energy based refrigeration system. One of the prominent green cooling technology is solar powered adsorption refrigeration system. The adsorption based cooling system is powered by low-grade heat including solar energy. The performance of the system relied on adsorption capacity of working pair, available heat sources and system components design. Limited investigation on the adsorption capacity of working pairs has been performed by various researchers. Adsorption refrigeration system can be used for space cooling, space heating, food preservation, vaccine storage, water chiller and ice making purpose. The study on the adsorption capacity of working pairs for water chiller application has been unattended.

Solar powered ice maker was proposed by Li and Sumathy [39] for household applications. AC-Methanol was used in adsorption refrigerator for producing 4-5 kg of ice per day with 0.92 $m^2$ collector area. Wang et al. [4] studied adsorption pair for cooling applications. In this experimental study, it was concluded that ACF-Methanol has higher COP, large adsorption capacity (0.68) and short cycle time compared to AC-Methanol. Satyapal and Sun [3] was investigated methanol adsorption on AC by using Micromeritics ASAP 2010 instrument. The adsorption capacity for ACF-Methanol is 0.38 and AC-Methanol are 0.24 due to the difference in BET surface area, pore volume, and adsorption heat. Anyanwu and Ogueke [40] studied the adsorption capacity of three different pairs for solar refrigeration application. The adsorption concentration was found for AC-NH3 is 0.19, AC-Ethanol is 0.19, and AC-Methanol is 0.23, isothermally during the experiment. ACF-Ethanol pair was experimentally studied by El-Sharkawy et al. [6] for application in adsorption cooling. The maximum adsorption capacity has been observed was 0.79 at an evaporator temperature of 10º C and generator temperature of 60 º C. They also studied the effect of apparent density and temperature distribution in adsorber bed.

Alghoul et al. [10] performed the experimental study on Malaysian AC for dual purpose solar adsorption system. The experiment was performed in the temperature range of 30-110º C and system pressure range of 3-25 kPa (vacuum pressure). The Observed concentration during the experiment is 0.36 ml/gm. In the review of adsorption working pairs, Wang et al. [11] described different methods of adsorption capacity measurement like volumetric method, liquid level measuring method and gravimetric method. The effect of generator temperature on adsorption capacity was investigated by Bhargav et al. [41] by considering isobaric adsorption.

In this research work, the adsorption capacity of ACF-Methanol, ACF-Ethanol and ACP - Ethanol has been investigated for solar powered adsorption water chiller. Activated carbon in pallet and fiber forms paid attention for its better adsorption properties. Methanol and ethanol have been proven refrigerant for solar adsorption chiller due to their low freezing point. The outcome of the study revealed its possible potentials for water chiller in household applications. Comprehensive experimental work on the adsorption capacity of ACF (Environ Care Product, India) and ACP (AURO Carbon & Chemicals, India) on methanol and ethanol have been performed respectively, which indicate the abundant possibilities of ACF- methanol as a new adsorption working pair for the water chiller. The physical properties of working pairs are received from the supplier is given in below Table 3.1.

**TABLE 3.1 Physical Properties of adsorbent and adsorbate**

| **Adsorbent** | **Surface Area ($m^2/g$)** | **Pore Size (Aº)** | **Density (g/cc)** |
|---|---|---|---|
| ACF | 1200 to 1700 | 16.87 | 0.444 |
| AC pallet | 500-1000 | 50-150 | 0.520 |

| **Adsorbate** | **Boiling Point (ºC)** | **Latent heat of Vaporization (kJ/kg)** | **Vapour Pressure ( kPa)** |
|---|---|---|---|
| Methanol | 64.6 | 1155 | 20 |
| Ethanol | 78.3 | 1020 | 12 |

(Value of Latent heat of Vaporization and Vapour pressure at 30 ºC)

The values of adsorption capacity investigated by different authors for a specific application is furnished in Table 3.2.

**Table 3.2 Adsorption capacity of activated carbon-based adsorption system**

| Author/s | Application | Working pair | Adsorption capacity |
|---|---|---|---|
| Wang et al [4] | Ice Maker | ACF-Methanol | 0.68 kg/kg |
| Jian Sun and Sunita Satyapal [3] | Heat pump | ACF-Methanol | 0.38 kg/kg |
| Anyanwu and Ogueke [40] | Solar Refrigeration | AC-Methanol | 0.23 kg/kg |
| El-Sharkawy et al. [7] | Cooling | ACF-Ethanol | 0.79 kg/kg |
| Alghoul et al. [10] | Dual purpose solar system | AC-Methanol | 0.36 ml/gm |

It is observed from Table-2 that ACF-Ethanol pair gives the maximum adsorption capacity while AC-Methanol pair has a minimum adsorption capacity. Hence it is concluded that ACF as an adsorbent has the potential for adsorption cooling system due to its higher surface area and large pore volume.

## 3.2 Experimental Set-Up:

For measurement of adsorption capacity of the ACF-methanol, ACF-ethanol and ACP-ethanol, the experimental set-up is designed & fabricated by considering isobaric adsorption process. The schematic diagram and photograph of experimental set up shown in Fig. 3.1 & 3.2 respectively. Isobaric adsorption and desorption occur at constant system pressure by varying temperature of adsorber bed and maintaining evaporator temperature. The experimental set up comprises of adsorber bed, connecting tube and evaporator. Two valves are used in setting up for vacuumisation/charging and between adsorber & evaporator. In this setup, the adsorbed refrigerant over activated carbon is measured by a level of refrigerant in the evaporator. The evaporator is of 2-inch diameter and 100 ml capacity having a transparent plastic cylinder. The rise and fall of refrigerant level exhibit the adsorption and desorption of refrigerant onto the adsorbent. In the experimental setup, the evaporator is connected to the adsorber bed through copper tubing.

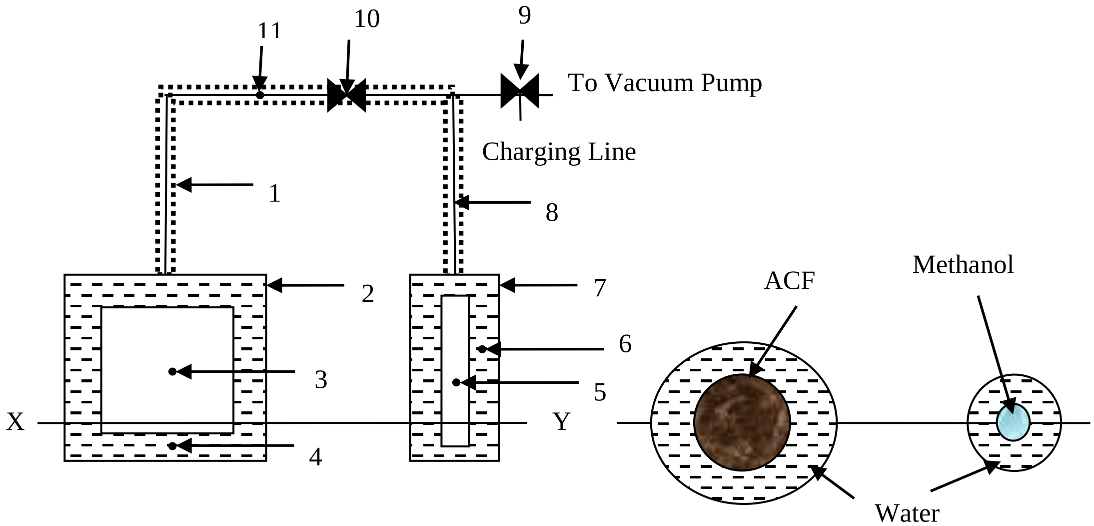


**Figure 3.1 Schematic diagram of experimental set up**

1:Tap heater; 2:Hot water tank; 3:Temperature sensor in adsorber; 4:Temperature sensor in hot water tank; 5:Temperature sensor in evaporator; 6:Temperature sensor in cold water tank; 7:Cold water tank; 8:copper connecting tube;9:Charging valve; 10:Controlling valve between adsorber and evaporator; 11:Temperature sensor on connecting tube

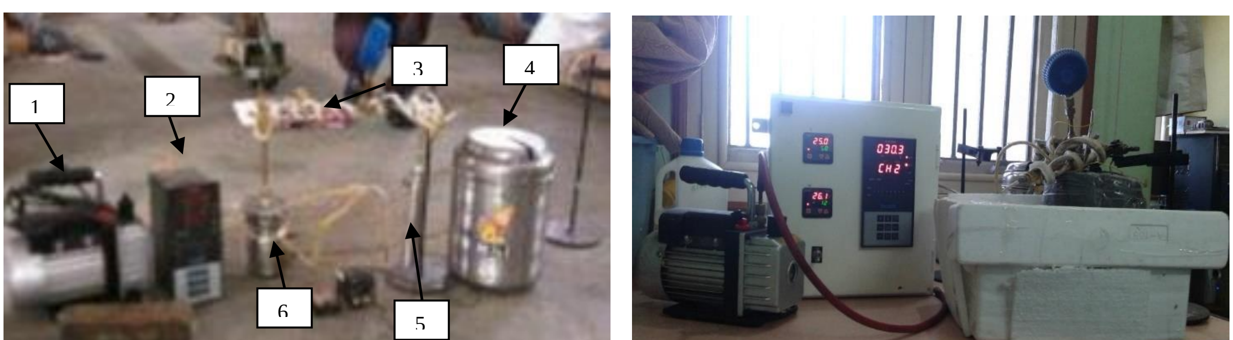


**Figure 3.2 Photograph of adsorption capacity measurement set up**

1: Vacuum Pump;2: Digital temperature scanner;3: Connecting tube with tap heater;4: Hot water tank; 5: Evaporator;6:Adsorber

To avoid condensation of refrigerant during the process electric tap heater wrapped on connecting tubes. The adsorber bed is made of stainless steel cylinder of 110 mm diameter and 150 mm length. Five thermocouples are inserted in adsorber, evaporator, hot water tank, cold water tank and on a connecting tube to measure the temperature during the process. Adsorber bed and evaporator are kept separately in a water tank for the effect of heating and cooling required for sorption.

## 3.3 Procedure:

For experimenting, following assumptions are made

1. Specific Heat & Density of adsorbent are constant
2. Adsorbent bed is composed of uniform size particles, and the bed porosity is constant
3. Heat transfer in the heating or cooling fluids and in the metal is one dimensional
4. No environmental effect & Steady state during observation

Before experimentation, the set-up is evacuated for a 10 kPa (vacuum) pressure and kept for 24 hours to confirm vacuum in the system. After the vacuum is retained in set up, the charging of refrigerant is performed. Once equilibrium is reached, open the valve placed on connecting tubes between bed and evaporator. Isobaric adsorption is achieved by maintaining the temperature of hot water bath placed outside adsorber bed through electric heater as well temperature of cold water bath placed outside the evaporator cylinder by adding ice cubes. The experiment begins with a high temperature of generator water to get better experimental results and then drop the temperature of the water, so adsorption of refrigerant effectively occurs on activated carbon base. System pressure is observed & recorded by calibrated dial type vacuum gauge which helps for maintaining tap heater temperature. Due to sudden adsorption of refrigerant over the adsorbent, there is an abrupt rise in temperature of adsorber observed initially by the liberation of adsorption heat. Reduction in temperature of bed accelerates the adsorption process, also refrigerant level in the evaporator cylinder shows the adsorption capacity for given working pair. The mass absorbed by unit mass of adsorbent represent the adsorption capacity of working pair.

## 3.4 Results and Discussion:

The adsorption capacity is measured by isobaric adsorption technique for three different working pairs for the solar-powered water chiller. The volume of adsorber cylinder decides the packing of ACF and ACP according to their density, hence lesser mass of ACF and higher mass of ACP is accommodated in adsorber bed. ACF sample (35 gram in weight) is used for methanol and ethanol adsorption. ACP weights 66 gram due to its low density to fill in adsorber bed. For adsorption capacity, the mass or volume adsorbed by the unit mass of activated carbon is to be taken, hence adsorbent mass is not important. As per volume available in adsorber bed, one should take the mass of adsorbent for experiments. For water chiller application, evaporator temperature is maintained at 20°C and adsorber temperature is varied to get isobaric adsorption during measurement. Among ACF-Methanol, ACF-Ethanol, and ACP-Ethanol, the maximum adsorption capacity is found in ACF-Methanol pair.

The Dubinin-Radushvevich equation is considered correlate the experimental data [10].

$$W = W_0 exp\left\{-D\lfloor Tln\left(\frac{P_S}{P}\right)\rfloor^n\right\}$$

The logarithmic form

$$ln(W) = ln(W_0) - D\lfloor Tln\left(\frac{P_S}{P}\right)\rfloor^n$$

$W_0$ and D can be obtained by fitting $ln(W)$ versus $\lfloor Tln\left(\frac{P_S}{P}\right)\rfloor^n$and at n=2 (DA Equation), the experimental data are best suitable.

Fig. 3.3 shows Isobaric adsorption of ACF/Methanol pairs [13]. The adsorbent temperature is gradually reduced from 80° C to 15° C at 68 cm of Hg vacuum pressure and measured the level of methanol in evaporator tube. From the figure, it can be noticed that adsorption capacity follows linear variation with adsorbent temperature. At the high temperature of Adsorber bed, less adsorption occurs and gradual reduction in temperature, the adsorption rate will increase. At low temperature 18° C to 20° C, the adsorption capacity will be maximum.

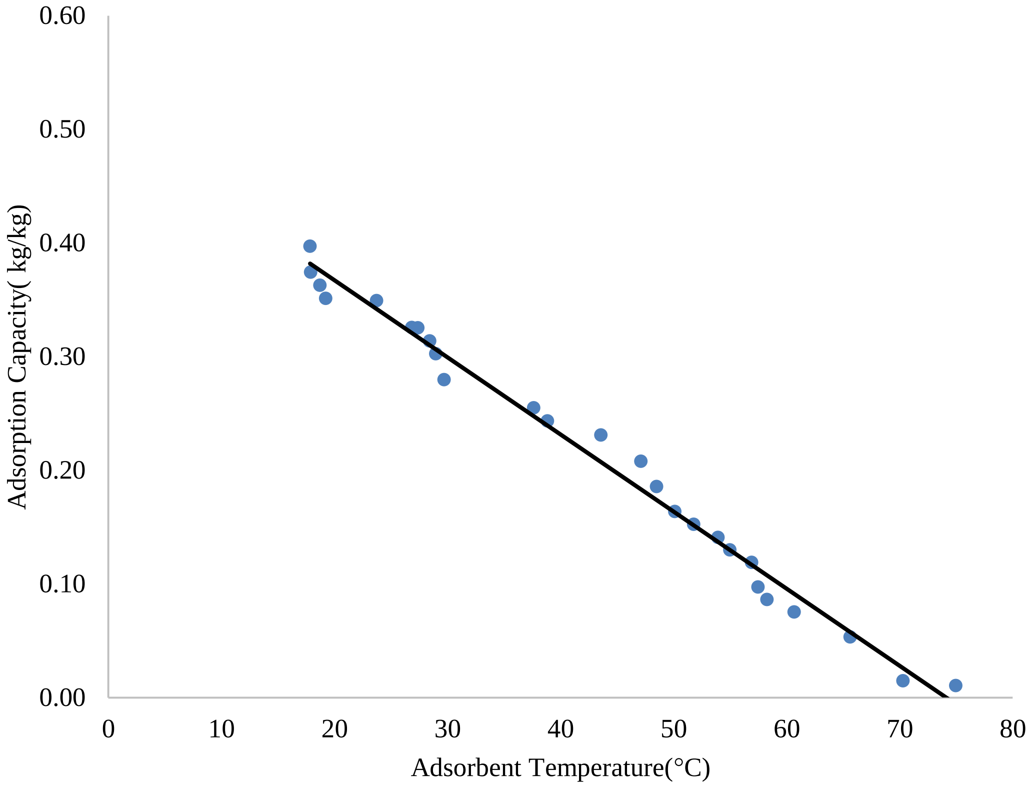


**Figure 3.3 Isobaric Adsorption of ACF/Methanol pairs**

The adsorption capacity of ACF-Methanol is 0.44 kg/kg, ACF-Ethanol is 0.28 kg/kg and ACP-Ethanol is 0.21 kg/kg. The higher adsorption capacity is due to uniform structure, higher porosity and large surface area provided by ACF to methanol. Methanol as a refrigerant in adsorption water chiller has a high latent heat of vaporization; low boiling point compares to ethanol and high vapour pressure which gives maximum adsorption capacity compared to ethanol. The variation in adsorption capacity of all the three pairs with time is shown in Fig.3.4.

The observed adsorption capacity of ACF-Methanol is 1.58 times and 2 times higher than ACF-Ethanol and ACP-Ethanol respectively. The higher adsorption capacity of ACF-Methanol confirms the lower mass of adsorbent compared to ACF-Ethanol and ACP-Ethanol which subsequently reduces the overall size of the water chiller. It also helps to reduce the cycle time of a cooling process. Fig.3.5 shows the isobaric adsorption of activated carbon with methanol and ethanol. ACF-Methanol responded in a large temperature range from 15-90°C, while other two pairs responded in a range of 15-60°C. This large range of adsorber temperature is convenient for selecting different source temperature. The adsorption capacity of ACF-Methanol pair has been measured and correlated with DR equation. Effect of adsorption temperature and time on adsorption capacity has been studied.

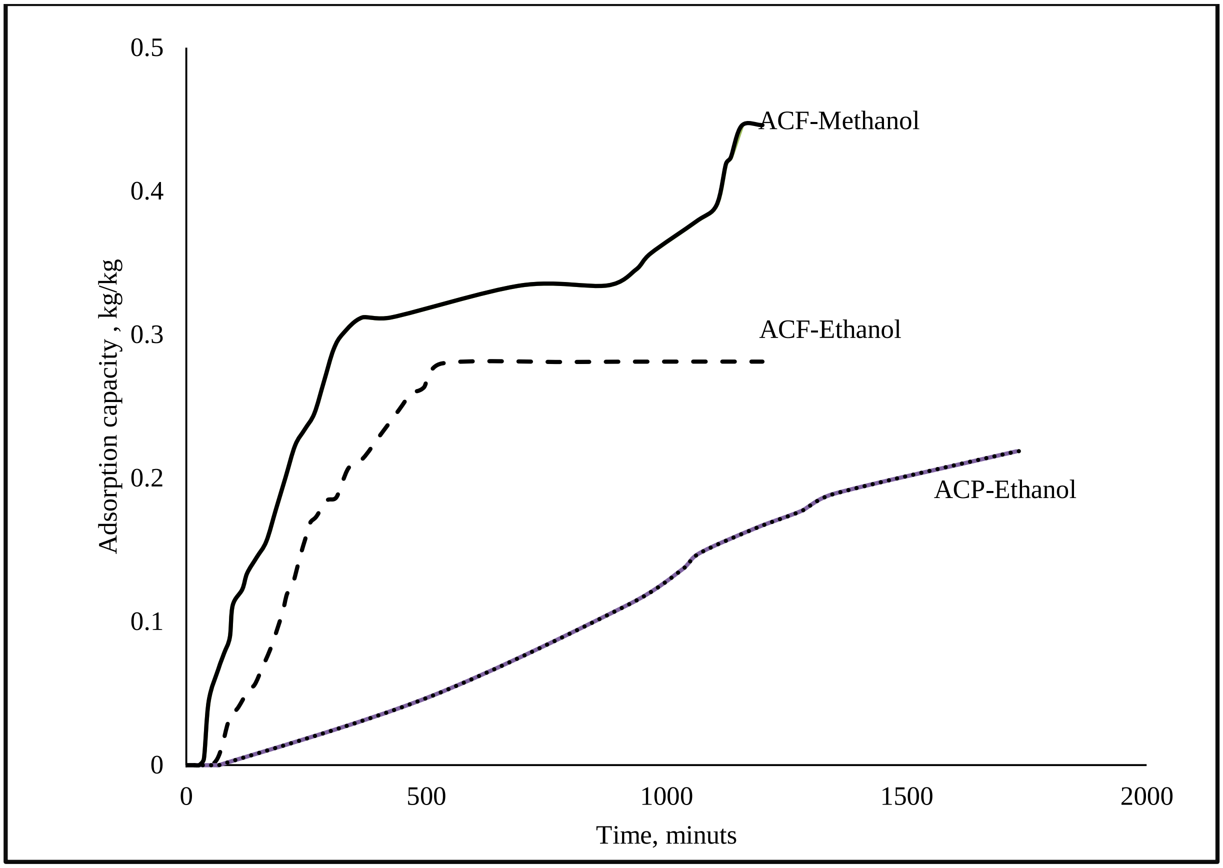


**Figure 3.4 Variation of adsorption capacity with time**

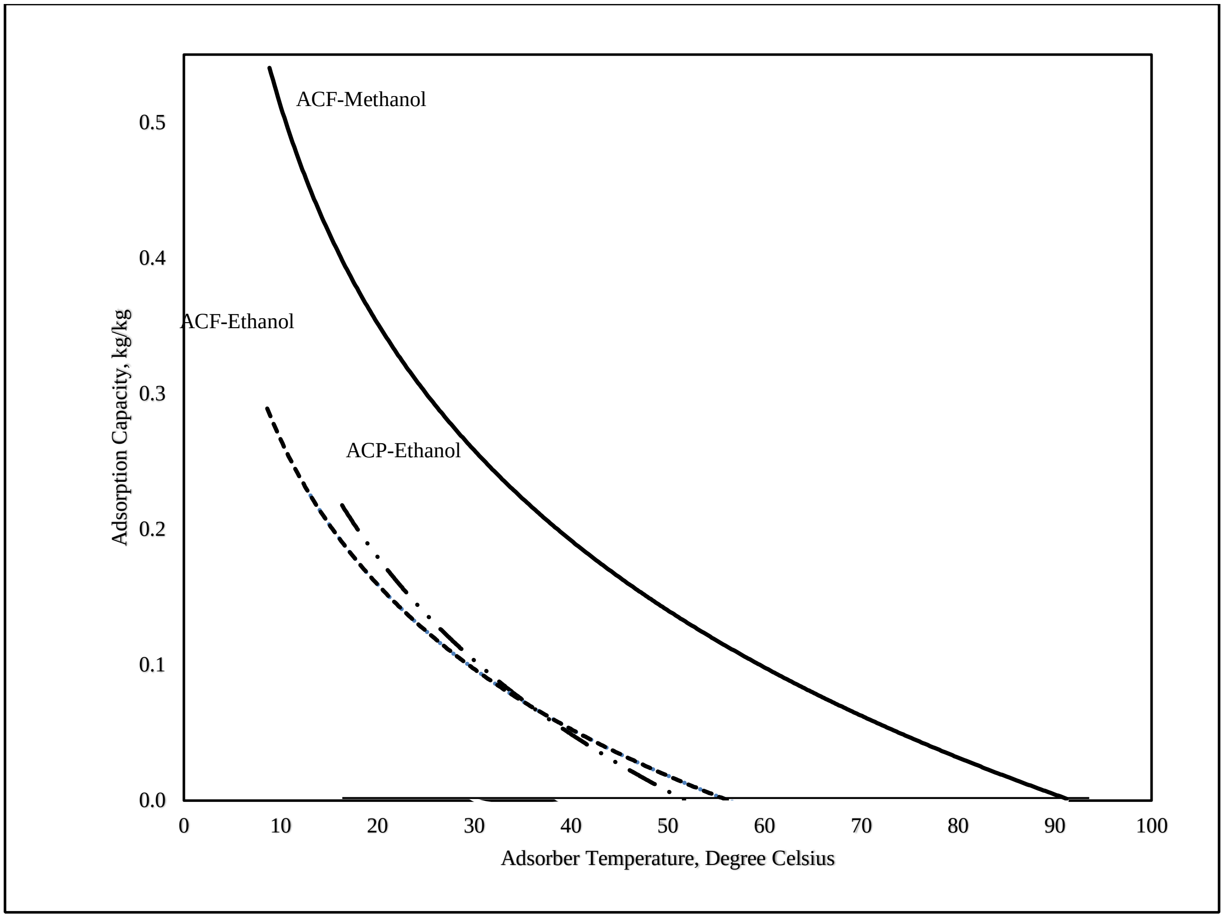


**Figure 3.5 Isobaric adsorption of activated carbon working pair**

Following outcomes are observed and recorded from this measurement

1. Adsorption occurs quickly in the first 900 seconds of adsorption cycle. As a result, temperature rises sharply due to the release of adsorption heat.
2. Higher adsorption rate is observed at 18 -20 °C.
3. High adsorption capacity at high relative pressure. ( 0.44 kg/kg at 0.48 )
4. Bed centre temperature is higher than top & bottom due to high thermal resistance.
5. ACF-Methanol adsorption cooling cycle utilized low-temperature heat (65 °C), which obtained from solar energy.

6. Adsorption equilibrium of methanol onto ACF have been experimentally investigated and found that D-R equation is the most appropriate adsorption isotherm model. Best linear fitting of D-R equation for ACF-Methanol pair at n=2, which considered as D-A equation.

7. ACF bed apparent density (110 kg/m3) affect the size of the system.

8. ACF has a large surface area (1500 $m^2$/gm) and uniform pore structure (16.87 A°), which gives better performance in adsorption cooling.

9. The value of Adsorption capacity (0.44 kg/kg) is relatively less which affect the size of chiller, i.e. system becomes bulkier.
10. Methanol is not compatible with copper and aluminium at high temperature (more than 120° C), also it reacts with a leak-proof adhesive which creates problems for vacuum.

## 3.5 Conclusion:

Solar assisted adsorption water chiller is a reliable option for a conventional water chiller. The experimental set up is developed for measuring adsorption capacity of the different working pair. ACF-Methanol has highest adsorption capacity than ACF-Ethanol and ACP-Ethanol due to better adsorption properties and low generation temperature. The difficulty facing with this pair is vacuum requirement and chemical reaction of methanol to human skin & eyes. The higher adsorption capacity of working pair reduces the size of the system and improves the overall performance of water chiller.

# CHAPTER 4

# Design of Hybrid Adsorption System

## 4.1 Introduction

From the literature survey, it was concluded that total cycle time for refrigeration is either 24 hours or few minutes',i.e. intermittent or continuous system. In this research work, the design and development of semi-continuous solar powered adsorption refrigeration technology are discussed,and ACF-Methanol has been selected as working pair for present design. The hybrid adsorption is consists of adsorber bed, condenser, capillary tube, evaporator and two water tank. Adsorption phenomenon with thermal aspects is used for the design of adsorption system components. It was decided to choose a standard water tank size (250-litre capacity) with an electrical heater for simulating solar water heater. The adsorbent (ACF) mass is considered by using adsorption capacity of the pair for necessary cooling effect and component sizing is calculated by heat balance analysis. The fixed parameters for the design of the system are cooling effect, ACF-methanol pair, hot/cold water temperature and condenser temperature. The purpose of the study is to develop a semi-continuous system (4 to 7 hours cycle time) with higher SCP (75 kJ/kg) operated by low generation temperature (65ºC). The proposed design of solar-powered adsorption chiller for food preservation has the potential to adapt for local cooling at farms for reducing spoilage of food before ittransfers to cold storage or market.

## 4.2 Materials and Methods

Adsorption chiller works on physiosorptionphenomenon in which adsorbate gathers over the surface of the adsorbent. In this phenomenon, adsorption processes occur due to lower temperature of adsorber bed (20 – 35 °C) and desorption due to the higher temperature of adsorber bed (60 – 90 °C) which is attainable by solar energy radiation.

The refrigeration is produced by repeated heating & cooling of adsorber bed by hot & cold water. The solar-powered Adsorption chiller consists of ETC, water tank (hot/cold), adsorber bed, condenser, evaporator and capillary tube. In the daytime, solar energy is collected by ETC and subsequently converted into hot water. By keeping separate hot and cold water tanks, adsorber bed obtains heating and cooling for system process.

**4.3 Design Process**

The design of adsorption refrigeration system relies on knowledge of chemical science, heat and refrigeration technology. With the physiosorptionprincipal and necessity of refrigerating effect, the design of the system isperformed. For food preservation, the temperature of storage system should be maintained at 10° C (i.e. vegetables and fruits can be preserved at this temperature for one or two weeks) [42]. An Adsorption chiller was designed for producing water temperature at 8-10 ° C in 4 to 6 hour. The cycle time for this whole process was 360 minutes, and hence it works as a semi-continuous system. The size of the system is decided by the adsorption capacity of adsorbent. For the adsorption capacity of the working pair, the experimental setup was developed,and the highest value observed out as 0.44 kg/kg, which is reported in the previous chapter.

The required mass of refrigerant is determined by the cooling effect and adsorption capacity. The gained mass decides the size of the chiller. In India as well as other parts of the world, the solar water heater is based on flat plate collector which can produce water temperature upto 55-70° C. Adsorption working pair is chosen in such a way that it will give satisfactory results at such low generation temperature. This system can easily be coupled with a solar water heater to give twin advantages of hot water and refrigerating effect [43].The system is designed in a way that is effective, economical and easesinmanufacture with readily available resources.

The design of adsorption chiller is based on the following assumption,

- Specific heat & density of ACF and methanol are constant
- Adsorbent bed is composed of uniform size
- Particles and the bed porosity is constant
- Heat transfer in the heating /cooling fluids and in the metal is one dimensional
- No environmental effect and steady state during operation

### 4.3.1 Mass of Methanol and ACF

The mass of methanol is determined by cooling requirement of product, i.e. water,

$$\mathrm{Q_{ref}} = m_w c_{pw} dT \tag{1}$$

And

$$m_{ref} = \frac{\mathrm{Q_{ref}}}{\mathrm{h_{fg}}} \tag{2}$$

Either by using Dubinin Astakhov correlation or physical measurement, the value of adsorption capacity is achieved.

$$x = \frac{m_{ref}}{m_{ads}} \tag{3}$$

From the above equation, the mass of ACF is calculated.

### 4.3.2 Adsorber bed Design

In this study, shell and tube heat exchanger is chosen for adsorber bed. From literature survey and heat transfer analysis, the shell and tube heat exchanger dimensions are calculated. In this research, diameter and length of shell and tube are given,and a number of the tubes is then calculated. Also, the mass flow rates, the temperatures of refrigerant and heat transfer fluid are identified. Using TEMA code [44] and heat transfer correlation, the final dimensions of the heat exchanger are available in Table4.1. The bed schematic and photograph is shown in Fig 4.1.

**Table 4.1. Calculated Dimensions for Adsorber Bed**

| Parameter | Specification |
|---|---|
| Heat Exchanger | Shell and tube type |
| Area | 0.22 $m^2$ |
| Shell | 154 mm in diameter,750 mm length |
| Tube | 9.5 mm in diameter, cu., |
| No. of tubes | 26 nos. |

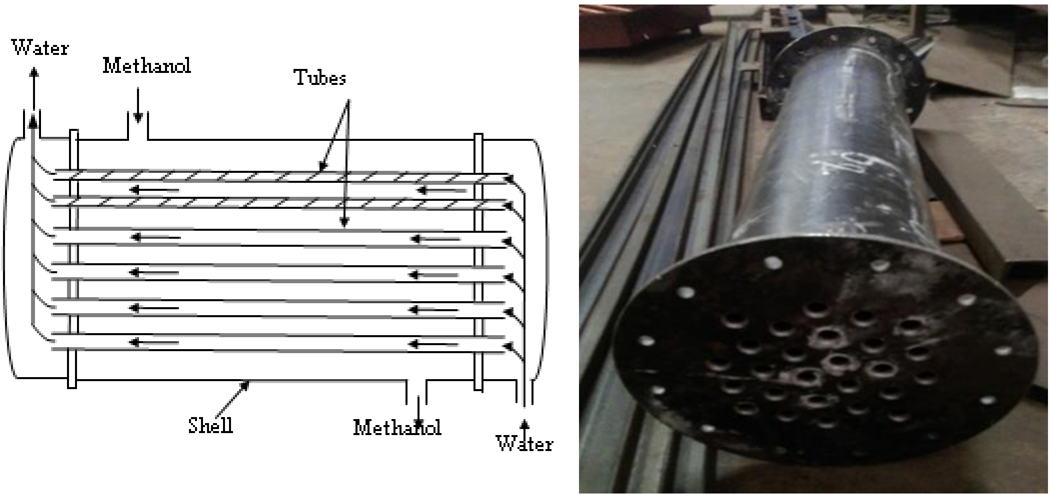


**Figure 4.1Shell and tube type adsorber bed**

Heat Duty in adsorber bed

$$Q_{ads} = m_m c_{pm} dT_m \tag{4}$$

Heat transfer coefficient, hi (h clean) for tube side is determined using Nusselt correlation,

Reynolds number is given as

$$Re = \frac{\rho u D}{\mu} \tag{5}$$

Apply for laminar flow

$$Nu = 0.332 Re^{0.5} \mathrm{Pr}^{0.33} \tag{6}$$

And

$$h_i = \frac{Nuk}{D} \tag{7}$$

$$h_i = h_{clean} \tag{8}$$

Calculate $h_{foul}$ by considering the effect of fouling factor,

$$R_f = \frac{1}{\mathrm{h_{foul}}} - \frac{1}{\mathrm{h_{clean}}} \tag{9}$$

The value of $R_f$ is 0.001 for city water (Standards of the Tubular Exchanger Manufacturers Association, 2007).Using theory of adsorbent thickness (≤ Ycritical) for better flow of methanol and ease in penetration, three layers of ACF is taken in the experiment [46]. For heat transfer from the tube fluid to shell refrigerant, four thermal resistance are involved- inside, cutube, ACF and outside [45]

$$R_i = \frac{1}{\mathrm{h_{foul}A_i}} \tag{10}$$

$$R_{cu} = \frac{\ln\left(\frac{\mathrm{R_o}}{\mathrm{R_i}}\right)}{2\pi \mathrm{k_{cu}L}} \tag{11}$$

$$R_{acf} = \frac{\ln\left(\frac{\mathrm{Ra_o}}{\mathrm{Ra_i}}\right)}{2\pi \mathrm{k_{acf}L}} \tag{12}$$

The overall heat transfer coefficient can then be expressedin terms of these four resistances,

$$\mathrm{U_o} = \frac{1}{(\mathrm{R_i} + \mathrm{R_{cu}} + \mathrm{R_{acf}} + \mathrm{R_o})\mathrm{A_o}} \tag{13}$$

and the area of the heat exchanger is calculated to be

$$A = \frac{\mathrm{Q_{ads}}}{\mathrm{U_o\ F\ LMTD}} \tag{14}$$

Where F is a correction factor and its value is unity [45]. From the area obtained, one can find the number of tubes for the heat exchanger. The radius of ACF must be less than the critical radius for better heat transfer and smaller pressure drop inside the tubes as well shell.The latter must be less than allowable pressure drop [45,47].

### 4.3.3 Condenser Design

The Water cooled heat exchanger is chosen as the condenser for the present study. In this configuration, the condensing effect is efficient, and there is flexibility to vary condenser temperature for experimentation. The final dimensions of the condenser are listed in Table 4.2. The schematic and image of the condenser are shown in Fig 4.2.

**Table 4.2 Calculated Dimensions for Condenser**

| **Parameter** | **value** |
|---|---|
| Heat Exchanger | Shell and Tube type |
| Area | 0.043 $m^2$ |
| Shell | Box type, 500 mm length, 500 mm width and 120 mm height |
| Tube | 12.7 mm diameter cu. ,1.5 m. length |

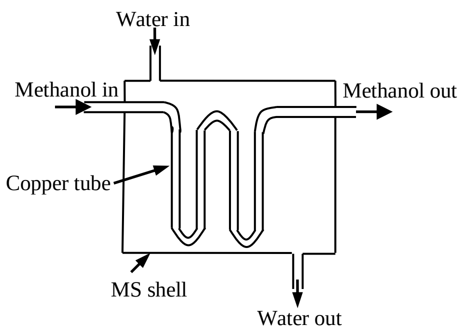


**Figure4.2 Water-cooled condenser**

Methanol vapour is coming from adsorber bed after desorption goes to a water-cooled condenser. The temperature and flow rate of methanol vapour depends on cycle time and generation temperature in the adsorber bed. Energy balance between methanol vapour and water in the condenser gives the area of tubes. In this work, quantity and flow rate of water in the condenser is given. The design calculation for the condenser is as follow [47], Heat capacity in condenser

$$Q_c = m_w c_{pw} dT \tag{15}$$

Considering counter flow arrangement in the condenser, the LMTD can be determined. For the overall heat transfer coefficient, first, calculate the tube side and shell side heat transfer coefficients,

Flow area per pipe

$$A_t = \frac{\pi}{4} D^2 \tag{16}$$

Mass velocity

$$G_t = \frac{m_w}{A_t} \tag{17}$$

Reynolds number

$$Re_t = \frac{DG_t}{\mu} \tag{18}$$

*Tube side heat transfer coefficient*

$$h_i = j_h \left(\frac{k}{D}\right) (c_p \mu / k)^{0.33} (\mu / \mu_w)^{0.14} \tag{19}$$

Where$j_h = (h_i D/k) (c_p \mu / k)^{0.33} (\mu / \mu_w)^{0.14}$

Including the thickness of tube, the corrected heat transfer coefficient is given by

$$h_{io} = \frac{h_i d_i}{d_o} \tag{20}$$

*Shell side heat transfer coefficient*

First, let us assume a shell side heat transfer coefficient ($h_o$) and by trial and error, fix it using the tube wall and condensate film temperatures.

The overall heat transfer coefficient ($U_c$) for a clean tube can be calculated by

$$U_c = \frac{h_i h_o}{h_i + h_o} \tag{21}$$

Consider the dust coefficient ($h_d$),

$$h_d = \frac{1}{R_d} \tag{22}$$

The overall heat transfer coefficient ($U_d$) is then given by

$$U_d = \frac{U_c h_d}{U_c + h_d} \tag{23}$$

Now the area required for the condenser tube ($A_c$) is given by,

$$A_c = \frac{Q_c}{U_d \text{ LMTD}} \tag{24}$$

The calculated area gives the total tube length for the fixed diameter of the tube in the condenser.

### 4.3.4 Capillary Tube Sizing

An adsorption refrigeration system with ACF-methanol as the working pair works under vacuum so that the capillary tube is sufficient to maintain the pressure difference in the system. The dimensions are calculated for the capillary tubes are summarized in Table 4.3. In the capillary tube, the pressure drop is due to friction and flashing effect. This pressure drop is directly proportional to the length of the tube and inversely proportional to its diameter.

**Table 4.3 Calculated parameters for Capillary tube**

| **Parameter** | **value** |
|---|---|
| Bore (D) | 2.54 mm |
| Mass flow Rate ( m°) | 0.00087 kg/sec |
| Mass Velocity ( G) | 171.69 kg/sec.$m^2$ |
| Length ( L) | 1142.52 mm |

The design of capillary tube implies selection of bore and calculation of length for maintaining the required flow at the given pressure difference between condenser and evaporator. Following is the design procedure for capillary tube:

For a given cooling load, identify the mass flow rate ($m_m$) of methanol. Select the bore ($D_{cap}$) size from available standard capillary size. Assume methanol is entering the capillary tube is a saturated liquid. At the condenser pressure, the temperature is $T_{c,}$ and at the evaporator pressure, the temperature is $T_e$. Now divide the temperature drop from $T_c$ to $T_e$ in a number of parts. The design steps based on isenthalpic flow are as follow [48],

Quality of methanol at the end of decrement,

$$x_1 = \frac{h'_c - h'_{f1}}{h'_{fg1}} \tag{25}$$

Calculate the specific volume

$$v_1 = v_{f1} + x_1 v_{fg1} \tag{26}$$

Determine the cross-sectional area of capillary

$$A = \frac{\pi}{4}(D_{cap})^2 \tag{27}$$

Determine the flow velocity by continuity equation

$$\frac{u}{v} = \frac{m_m}{A} = G \tag{28}$$

$$u_c = m_m \frac{V_c}{A} \tag{29}$$

And $$u_1 = m_m \frac{V_1}{A} \tag{30}$$

By iterations, one obtains $h_1$ for the Fano line flow

$$h'_1 = h'_c - \frac{{u_1}^2}{2} \tag{31}$$

Calculate the pressure drop by momentum equation

$$\Delta P_a = \frac{m_m}{A}(u_c - u_1) = G\,(u_c - u_1) \tag{32}$$

Determine the pressure drop due to friction

$$\Delta p_f = \Delta p - \Delta p_a \tag{33}$$

Now relate the pressure drop to friction factor,

$$\Delta p_f = (\rho f L u^2)/(2D) \tag{34}$$

Simplify the equation to give

$$\Delta p_f = Y f u \Delta L \tag{35}$$

Where Y= (G/2D) and f = ($0.324/Re^{0.25}$)

In this way, $\Delta L$ is calculated and summation of $\Delta L$ will give thetotal length of the capillary tube.

### 4.3.5 Evaporator Design

After reviewing literature for water chiller, it is found that immersion coil type heat exchanger is the best configuration. The mass of methanol and quantity of product decide the size of the heat exchanger. Thermal and mechanical design of coil type heat exchanger has performed accordingly.The final dimensions obtained are shown in Table 4.4.

**Table 4.4 Calculated Parameters for Evaporator**

| **Parameter** | **value** |
|---|---|
| Heat Exchanger | Shell and coil type |
| Area | 0.24 $m^2$ |
| Shell | 200 mm in diameter, 400 mm high |
| Tube | 12.7 mm in diameter, 6 m. long |

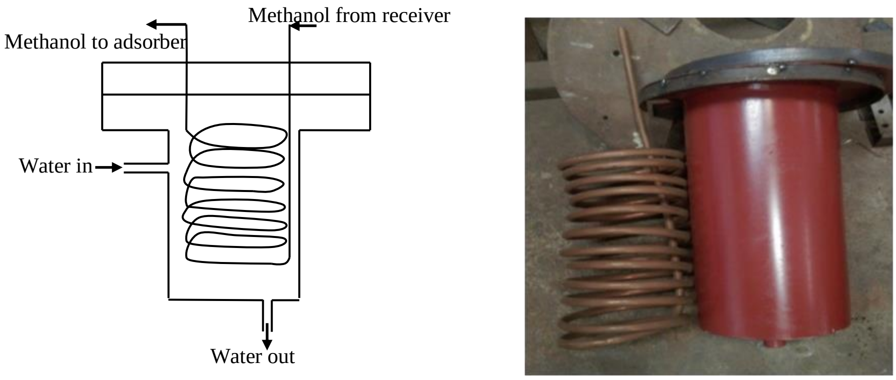


**Figure 4.3 Immersion coil type evaporator**

The schematic and photograph of the evaporator are shown in Fig 4.3. The helical coil heat exchanger is best suited for laminar flow and limited space. The design of helical coil and shell is determined by the mass velocities of the fluids. The following are the steps in the design of evaporator [49].

Calculate the overall heat transfer coefficient

For laminar flows, the shell side heat transfer coefficient ($h_o$) is given by,

$$(h_o \frac{D_e}{k}) = 0.6\,(Re)^{0.5}(Pr)^{0.31} \tag{36}$$

And the tube side heat transfer coefficient ($h_i$),

$$h_i = j_h \left(\frac{k}{D}\right)(Npr)^{0.33} \tag{37}$$

Now, the corrected tube side coefficient ($h_{io}$) is given by,

$$h_{io} = \frac{h_i D}{D_o} \tag{38}$$

The overall heat transfer coefficient

$$\frac{1}{U} = \frac{1}{h_o} + \frac{1}{h_{io}} + \frac{x}{k} + R_c + R_s \tag{39}$$

Where x is the coil thickness, k is the thermal conductivity of coil metal, $R_c$& $R_s$ are the fouling factors for coil and shell respectively.

Now the area required for the helical coil is

$$A_{coil} = \frac{Q_{ref}}{U\ LMTD} \tag{40}$$

Where $Q_{ref}$ is the cooling load in the evaporator. The calculated area gives the total tube length required for the evaporator.

The heat transfer fluid is water which is 250 litre in capacity. Two separate tanks are provided for hot and cold water which is supplied in a cycle to the bed as shown in Fig.4.4. Water tanks and other equipment are enclosed with insulation. The specifications of insulation are listed in Table 4.5. The final calculated dimensions with specifications of adsorption chiller are summarized in Table 4.6.

**Table 4.5 Specifications of Insulation**

| Insulation Cover | Specification |
|---|---|
| Water Tank | Rock Wool, density 48 kg/ $m^3$ , 100 mm thick |
| Evaporator | Puf, density 40 kg/ $m^3$, 50 mm thick |
| Condenser | Rock Wool, density 48 kg/ $m^3$ , 50 mm thick |

**Figure 4.4 Hot and cold water tank**

**Table 4.6 Final Specification of Adsorption chiller**

| Component | Type | Specification |
|---|---|---|
| Adsorber bed | Shell and tube | Shell:<br>154 mm in diameter, 750 mm long<br>Tube: 3/8 inch cu. ,26 tubes |
| Evaporator | Helical coil immersion water cooled | Shell-12 L<br>Tube: ½ inch cu.<br>6 m long,11turns, 19.05 mm in pitch |
| Condenser | Shell and tube<br>Water cooled | Box type shell- 25 L<br>Tube: ½ inch cu. , 1.5 m long |
| Hot/cold water tank | Cylindrical insulated tank | 250 L capacity metal tank with insulation |
| Expansion device | Capillary tube | 2.5 mm bore<br>1.2 m long |

## 4.4 Equipment Description

The schematic diagram and photograph of semi-continuous solar powered adsorption chiller are shown in Fig. 4.5 and Fig. 4.6. This system comprises a hot water tank with temperature regulator to simulate the solar water heater. With this arrangement, experimentation can be conveniently conductedat any time and any location for simulated conditions. For precise control, there was a thermostat with temperature relay attached to a water tank. With this arrangement, manual control in the mass flow rate of water and temperature control of hot water and cold water is possible.

Also, the frequency of water supply (hot water timing / cold water timing) is maintained. For measuring the temperature at different locations of the system, calibrated K type thermocouples were installed. Dial pressure gauge was used to provide system pressure during operation. There was also temperature controller provided in the condenser to monitor the real conditions. The reduction in temperature of water kept in the evaporator shell gave cooling effect produced in each cycle. The overall system is developed for better cooling effect and identified the best combination of parameters for efficient performance. To measure the drop in evaporator temperature, cyclic heating & cooling of adsorber bed is required for a specific time. Heating is observed in adsorber bed by supplying hot water and cooling is by tap water. The fixed parameters are the temperature of hot & cold water, the frequency of water supply and mass flow rate of water to achieve the desired cooling effect in water.

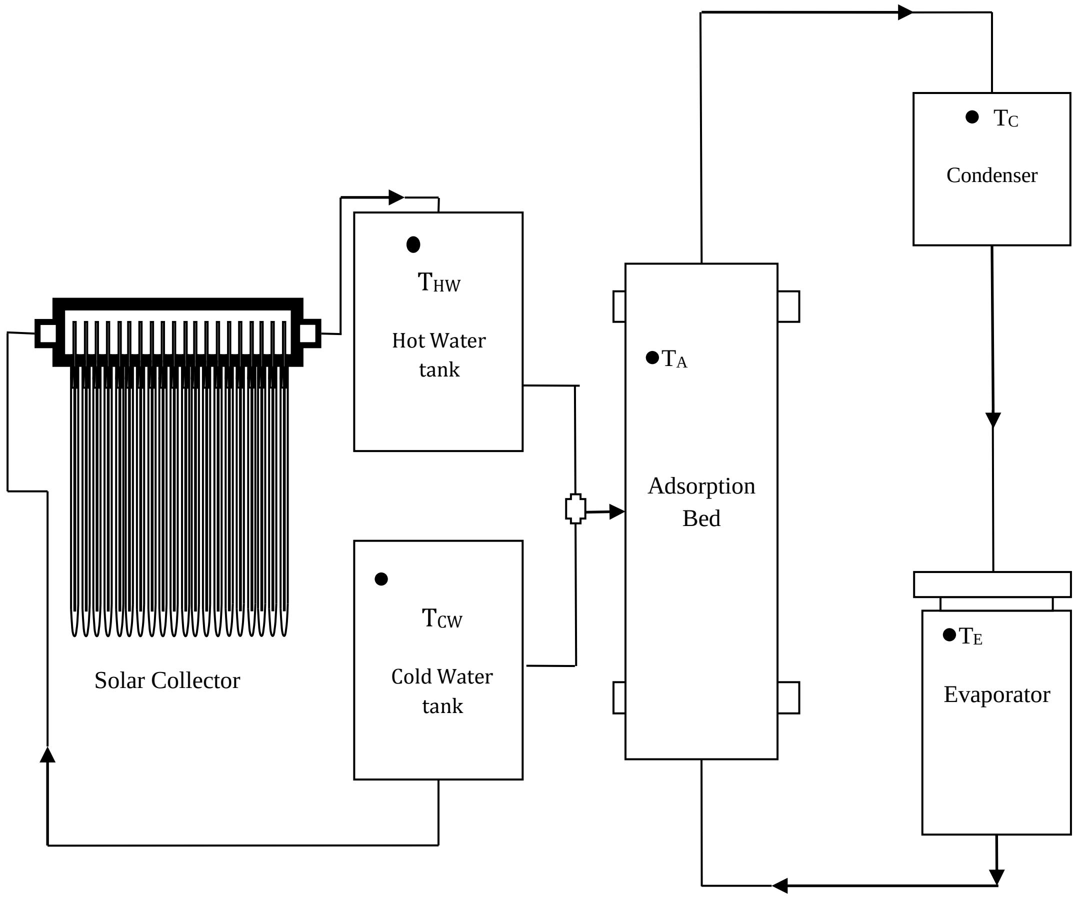


**Figure 4.5 Schematic diagram of Adsorption water chiller**

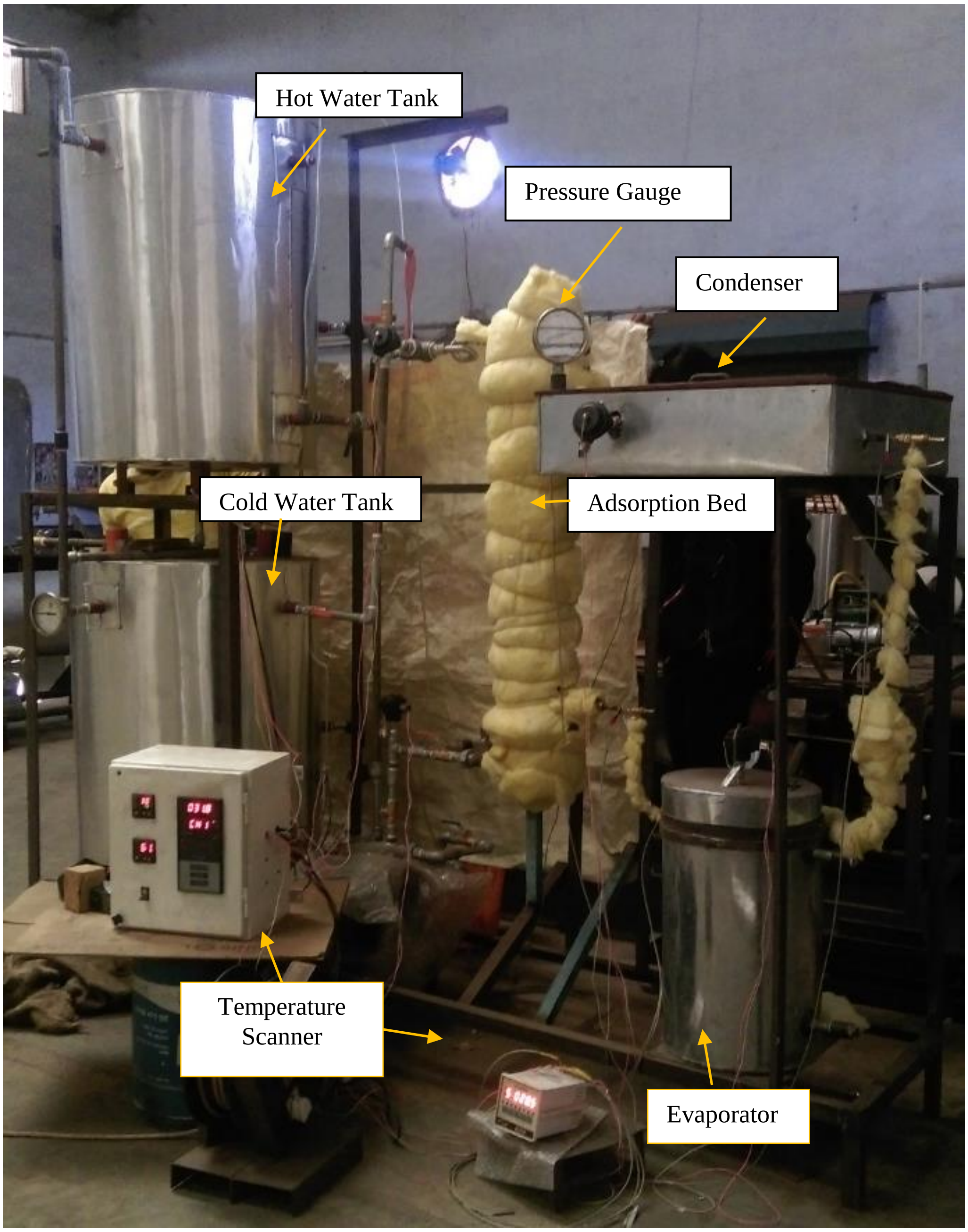


**Figure4.6 Photograph of Adsorption Chiller**

# CHAPTER 5

# Experimental Investigation and Performance Analysis

## 5.1 Introduction

In this research work semi-continuous solar powered Adsorption water chiller has been developed for cooling of 10 kg water in 3 hours with a temperature drop of 10° C. The design of the main components include adsorber bed, condenser, an expansion device and evaporator of adsorption water chiller. For experiment purpose, an electrical heater is used in a hot water tank to simulate solar-powered water heater. This arrangement gives controlled temperature and flexibility throughout the experimentation schedule. With 63 °C generator temperature, 27 °C condenser water temperature, and 33°C cold water temperature, the highest value of specific cooling power (SCP-75.4 W/kg) and COP (0.45) have been achieved. The mass of activated carbon fiber (ACF) is 450 gram, which reduces the size of adsorber bed and charged methanol is 650 ml, which reduces the size of an evaporator, condenser, and tubing. Hence with the small size refrigeration system, effective cooling is produced by solar energy through ETC collector. By series of experiment, an appropriate working environment has been suggested for better performance.

## 5.2 Design of Experiments (DOE)

The ACF-Methanol based semi-continuous adsorption chiller has been designed and develop by considering the input factor as Hot water temperature, Cold water temperature, Water flow rate and Frequency (ratio of time of hot water to cold water supply) for getting a response in terms of COP and SCP. Figure 5.1 shows the DOE of the system.

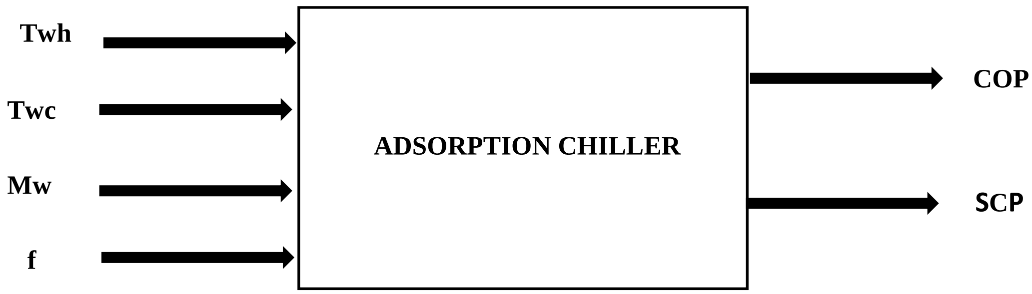


**Figure 5.1. DOE of semi-continuous adsorption chiller**

The two key performance parameters for adsorption chiller are the coefficient of performance (COP) and specific cooling power (SCP). The refrigerating effect in terms of the drop in evaporator temperature per unit electrical energy supplied to heater gives the COP and refrigerating effect per unit mass of ACF gives the SCP of the proposed chiller. The following are formula for COP and SCP

Coefficient of Performance (COP): Qref / Qgen,

Specific Cooling Power (SCP): Qref / (Macf ·Cycle Time)

Where Qref is refrigerating effect, Qgen is total energy input to the electrical heater, and Macf is a mass of ACF.

Following parameters have been measured and monitored in experimentation

- Temperature of Hot Water (Tg)
- Temperature of Cold Water ( Ta)
- Temperature of Water in condenser (Tc)
- Temperature of  Water in Evaporator (Te)
- Mass flow rate of Water from Tank to Adsorber Bed
- Vacuum Pressure of System

The temperature at different locations is measured by calibrated K type thermocouples. In hot & cold water tank, relays are kept for controlling the temperature of water. The Mass flow rate of water is measured by stopwatch and measuring cylinder, and system pressure is measured by Pressure gauge. All temperature sensors are connected to temperature scanner for monitoring the data.

The fixed parameter in all experiments is cooling capacity ($Q_r$), adsorption capacity (X) and working Pair-ACF/methanol.

The refrigerating effect is calculated by calorimeter principle, i.e. the product of the mass of water available in evaporator vessel, the specific heat of water and drop in temperature of water.

$Q_r = M_w \cdot C_{pw} \cdot \Delta T$

And Qgen (Total Energy Input) is measured by Electrical Energy hour meter in the form of kWh. The hour meter gave the energy consumed during the cycle.

The schematic diagram of the experimental setup is already presented in the previous chapter in which solar collector is simulated by the electric water heater. This arrangement gives control over the hot water temperature and time of the experiment.The overall system is designed and developed for better cooling effect and to identify the best combination of a parameter for efficient performance. The photograph of semi-continuous solar powered adsorption chiller is shown in Figure 6(Chapter 4). This system consists of a hot water tank with the temperature controller to simulate solar water heater. With this arrangement, there is a convenience for experimentation at any time and at any location for simulating conditions.

To identify best working environment of semi-continuous solar power adsorption water chiller, series of experiments performed by varying different parameters like hot water temperature, cold water temperature, a flow of water, time of supply (hot water and cold water) etc. During experiments, drop in temperature of water available in the evaporator is observed as a cooling effect. The important performance parameters SCP and COP are obtained by cooling effect and electric input to the water heater. It is observed a fluctuation in system pressure due to cyclic heating and cooling of bed by hot & cold water. After heating cycle, the system needs to be cool down for next adsorption cycle. By performing parametric analysis, it is found that best COP and SCP can be achieved by low generation temperature (60 -80 ° C) which can achieved by solar collectors. The experimental conditions are shown in Table5.1.

**Table 5.1 Experimental conditions**

| Sr.No. | Parameters | Range |
|---|---|---|
| 1. | Hot water temperature | 40-84 ° C |
| 2. | Cold water temperature | 30-41 ° C |
| 3. | Condenser temperature | 25-33 ° C |

### 5.2.1 Assumption

Following assumptions are made during experiment

1. No Environmental Effect during Experiments.
2. Steady-state during observation
3. Specific heat of water remains constant during operation.
4. No variation in mass flow rate and frequency of water supply.
5. All measuring instruments show actual parameters.
6. Total Energy supplied by the electrical heater is fully utilized by water for heating.
7. The mass flow rate of water during a set of experiment is remains constant.

## 5.3 Procedure of Experiment

The following procedure is made for performance evaluation of the adsorption chiller.

1. Set the hot water and cold water temperature ( i.e. 65 and 30 °C)
2. Set the frequency of hot water to cold water supply (i.e. 10 min hot water / 30 min cold water)
3. Set the mass flow rate of hot water and cold water ( i.e. 200 kg/hr)
4. Allow hot water to adsorber bed for 10 min and measure the temperature at various point by digital scanner ( Hot water temperature, Cold Water temperature, Evaporator water temperature, Condenser water temperature and methanol temperature at various point)
5. Measure mass flow rate of hot water by cylindrical beaker and stopwatch
6. Measure system pressure by dial type vacuum gauge.
7. Allow heating cycle for specific, predefined time.
8. Switch to cooling cycle by supplying cold water to bed and follow same step 4 to 6
9. Allow heating and cooling cycle for a predefined time and note down the temperature drop in evaporator water.

**Table 5.2 Sample Observation**

| Date | Time | Cycle (Heating/ Cooling) | Pressure (mm of Hg) | Flow Rate (kg/hour) | Average Hot Water Temp | Average Cold Water Temp | Evaporator Water Temp. (Degree C) |
|---|---|---|---|---|---|---|---|
| 22/2/17 | 6.30pm | H | 490 | | 49.45 | 29.55 | 28.2 |
| | 6.40 | H | 370 | 177 | 49.3 | 30.95 | 28.3 |
| | 6.55 | C | 475 | 150 | 53.75 | 32.05 | 27.9 |
| | 7.10 | C | 475 | | 57.9 | 33.8 | 27.3 |
| | 7.20 | H | 300 | 144 | 57.95 | 34.05 | 26.9 |
| | 7.35 | C | 475 | 142 | 61.95 | 34.35 | 26.5 |
| | 7.50 | C | 475 | | 64.4 | 34.45 | 25.7 |
| | 8.00 | H | 210 | 206 | 63.2 | 34.55 | 25.6 |
| | 8.15 | C | 475 | 220 | 64.4 | 34.55 | 25 |
| | 8.30 | C | 475 | | 64.25 | 34 | 24.5 |
| | 8.40 | H | 225 | 202 | 61.3 | 34.4 | 24.6 |
| | 8.55 | C | 475 | 170 | 61.25 | 34.3 | 24.1 |
| | 9.10 | C | 475 | | 61.2 | 34.35 | 23.8 |
| | 9.20 | H | 280 | 150 | 59.05 | 34.3 | 23.6 |
| | 9.35 | C | 475 | 170 | 60.2 | 34.25 | 23.5 |
| | 9.50 | C | 475 | | 60.1 | 34.4 | 23 |
| | 10.00 | H | 265 | 165 | 59.65 | 34.55 | 22.6 |
| | 10.15 | C | 475 | 215 | 60.1 | 34.45 | 22.4 |
| | 10.30 | C | 475 | | 60.05 | 34.55 | 21.7 |
| | 10.40 | H | 300 | 205 | 59.2 | 34.6 | 21.7 |
| | 10.55 | C | 475 | 222 | 60.35 | 34.6 | 21.2 |
| | 11.10 | C | 475 | | 60.25 | 34.55 | 20.8 |
| | 11.20 | H | 275 | 160 | 60.2 | 34.6 | 20.7 |
| | 11.35 | C | 475 | 221 | 60.4 | 34.55 | 20.1 |
| | 11.50 | C | 475 | | 60.3 | 34.5 | 20 |
| | 12.00 | H | 290 | 171 | 59.65 | 34.6 | 20 |
| | 12.15 | C | 475 | 221 | 60.5 | 34.6 | 19.8 |
| | 12.30 | C | 475 | | 60.5 | 33.8 | 19.2 |
| | 12.40 | H | 250 | 262 | 59.9 | 33.85 | 20.1 |
| *H-Heating cycle, C –Cooling cycle* | | | | | | | **9.1** |

### 5.4 Outcomes from observation

Following conclusion are made from sample observation Table 5.2

- Temperature drop in evaporator water is 9.1 °C
- Frequency of hot water to cold water supply is 10 min to 30 min
- Average mass flow rate of hot water and cold water is 150 kg/hr
- The system pressure varies between 285 and 510 mm of Hg during heating and cooling cycle.
- Overall cycle time is 6 hours
- Drop in evaporator water temperature follow staircase pattern due to heating and cooling cycle for desorption and adsorption process. By keeping large cycle, higher drop in evaporator temperature can be achieved. The drop in evaporator temperature (Cooling Effect) is shown in Fig. 5.2.

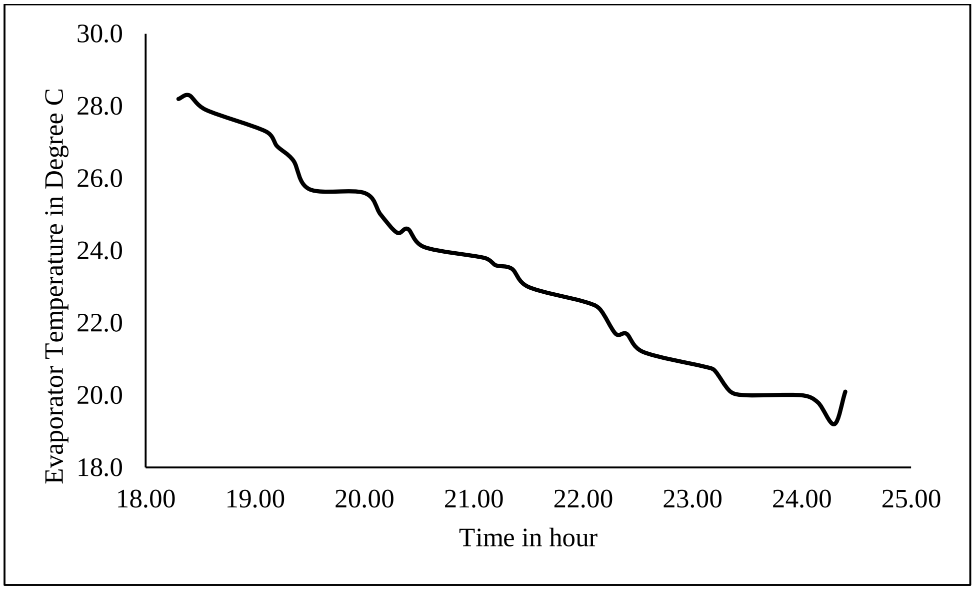


**Figure 5.2 Drop in Evaporator Temperature with Time**

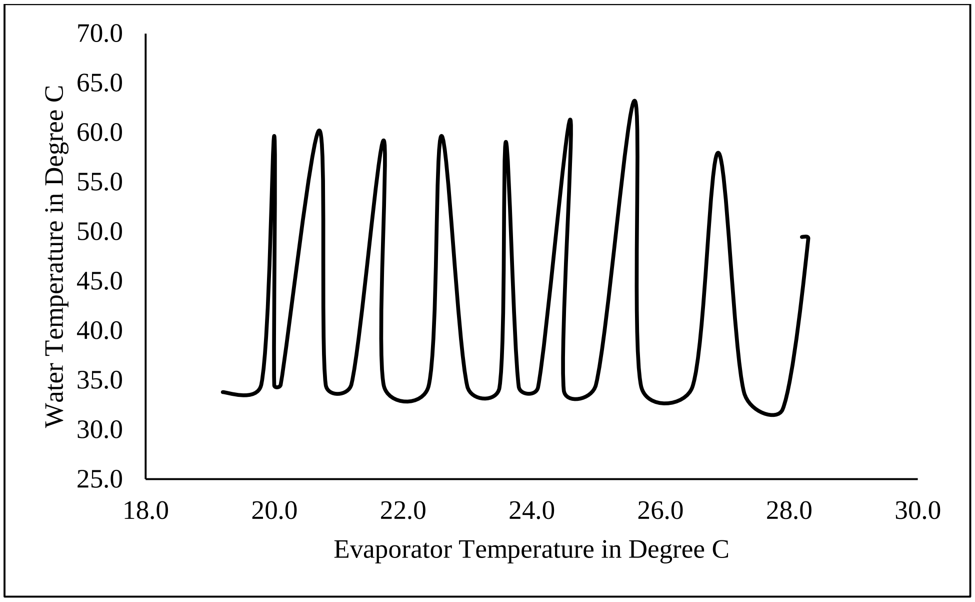


**Figure 5.3 Effect of Water Temperature on Evaporator Temperature**

- Drop in evaporator water temperature follow hill-valley pattern due to heating and cooling cycle for desorption and adsorption process. The effect of hot and cold water on evaporator water is shown in Fig. 5.3.
- As generator temperature rises, the steady drop occurs in evaporator temperature which concludes that a high generator temperature can produce the better cooling effect which shown in Fig. 5.4.

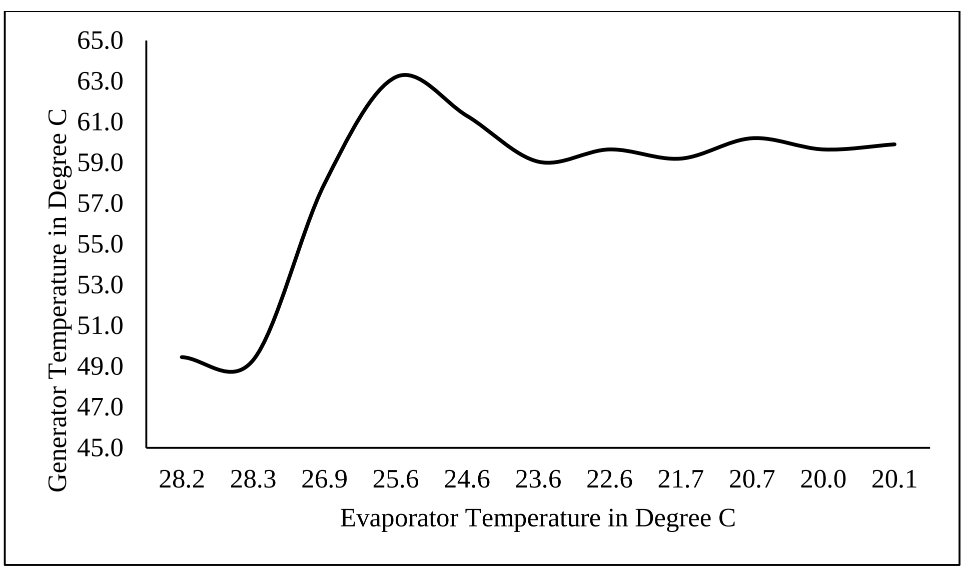


**Figure 5.4 Effect of Generator Temperature on Evaporator Temperature**

**Table 5.3 Summary of observations**

| Date | Frequency ($t_{wh}/t_{wc}$) min/min | Pressure ( mm of Hg) Adsorption | Desorption | Mass flow rate of water (kg/hr) Hot | Cold | Water Temp (°C) Tg | Ta | Condenser Temp (°C) | Evaporator Temp (°C) | Del T |
|---|---|---|---|---|---|---|---|---|---|---|
| **07/02/17** | 30 /60 | 220 | 750 | 600 | 600 | 85 | 36 | 33 | 24 | **16** |
| **09/02/17** | 60/120 | 215 | 710 | 400 | 400 | 64 | 30 | 28 | 23 | **11.7** |
| **10/02/17** | 60/150 | 220 | 435 | 600 | 600 | 54 | 31 | 27 | 25 | **4.5** |
| **11/02/17** | 20/30 | 240 | 600 | 140 | 140 | 62 | 32 | 28 | 20 | **8.9** |
| **17/02/17** | 15/15 | 260 | 480 | 130 | 130 | 58 | 34 | 26 | 25 | **3.8** |
| **18/02/17** | 10/30 | 280 | 540 | 220 | 220 | 66 | 34 | 26 | 24 | **5.6** |
| **20/02/17** | 10/30 | 285 | 640 | 200 | 200 | 67 | 34 | 27 | 23 | **5.9** |
| **22/02/17** | 10/30 | 285 | 510 | 150 | 150 | 60 | 34 | 25 | 19 | **9.1** |
| **28/02/17** | 10/30 | 215 | 470 | 240 | 240 | 58 | 30 | 26 | 22.4 | **6.6** |
| **03/03/17** | 5/15 | 236 | 435 | 715 | 715 | 55 | 41 | 27 | 22.7 | **6** |
| **04/03/17** | 10/30 | 240 | 571 | 664 | 664 | 62 | 30 | 28 | 22.7 | **8.6** |
| **08/03/17** | 10/30 | 243 | 286 | 805 | 805 | 40 | 30 | 26 | 23.1 | **5.4** |
| **09/03/17** | 10/30 | 244 | 375 | 888 | 888 | 49 | 30 | 26 | 22.5 | **5.8** |
| **11/03/17** | 10/30 | 322 | 628 | 808 | 808 | 64 | 31 | 31 | 20.8 | **8.8** |
| **14/03/17** | 10/30 | 282 | 450 | 177 | 177 | 60 | 34 | 25 | 23 | **11.7** |
| **15/03/17** | **10/30** | **244** | **485** | **360** | **360** | **63** | **33** | **27** | **25** | **10.9** |
| **20/03/17** | 10/30 | 275 | 460 | 173 | 173 | 60 | 34 | 25 | 24 | **12.1** |
| **22/03/17** | 10/30 | 277 | 440 | 172 | 172 | 60 | 34 | 25 | 24 | **13.2** |

*Tg- Generator Temperature (Hot water), Ta- Adsorption Temperature (Cold Water)*

*DelT- Temperature drop in Evaporator water*

## 5.5 Outcomes from Summary of Observation

The summery of all observation is mentioned in Table 5.3.It is observed from the observation summary that with this proposed system, water temperature can be reduced by 16°C with generation temperature of 75°C. The performance of the system in term of cooling production is carried out at a different combination of frequency, mass flow rate, and hot/cold water temperature is shown in summary table. In this table, only drop in evaporators water temperature is focused which doesn't prove the system performance. It is also necessary to discuss the COP and SCP with cooling production which gives the exact performance of the system. In chapter 6, Results and Discussion is deliberated in details.

## 5.6 Difficulties Observed During Experiment

Following difficulties are found during development and experimentation

- Mounting of ACF on copper tubes,
- Maintenance of vacuum though out experiment,
- Charging of methanol into the system,
- Control of the hot/cold water flow,
- Optimization of cycle time,
- Environmental effect,
- Response of measuring instruments,
- Cooldown period of system
- Periodic observation
- Methanol compatible adhesive

# CHAPTER 6

# Results and Discussion

## 6.1 Introduction

The hybrid solar powered water heater and adsorption refrigeration system were developed, and experiments were performed on it. The adsorption capacity of three different pairs is investigated, and the best pair is selected among them which is described in Chapter 3. The experimental investigation is carried on set-up where an effect of generation temperature and frequency of water supply on evaporator temperature is studied & discussed in Chapter 5. In this chapter, critical observations made during experimentation are discussed with their results have been compared with existing work on the solar refrigeration system.

## 6.2 Results

The developed experimental set up was operated for data collection during February – March 2017 in Anand, Gujarat (India) for selecting best generation temperature and frequency of water supply to semi-continuous adsorption water chiller.  The experiment aims to identify best working environment for the same system. In the experiment, the generation temperature is simulated by hot water tank powered by electrical heater instead of the solar water heater. This arrangement provides flexibility for the experiments. The frequency, i.e. time of hot water supply to the time of cold water supply in adsorber bed, is maintained by 0.55 kW capacity horizontal centrifugal pump. With pump arrangement, the system can operate at the different flow rate of water by a manual control valve. For calculation of performance parameter, the electrical power consumed by the pump is considered by using hour meter in the set-up. The cold water supply in adsorber bed for adsorption is taken from tap water. These two arrangements, electrical heater and pump can be replaced in real field applications of this chiller with solar FPC/ETC water heater and solar pumping system. Table 6.1 represents the performance parameter based on an experimental investigation in previous Chapter 5.

**Table 6.1 Result (Day wise)**

| Date | Cooling Effect (kJ) | SCP (kJ/kg) | Total Time (hour:min) | SCP (W\kg) | Cooling Effect (W) | Input Power (W) | COP |
|---|---|---|---|---|---|---|---|
| 7th Feb’17 | 672.00 | 1493.30 | 9 :15 | 44.80 | 20.18 | 180.00 | 0.11 |
| 9th Feb’17 | 491.40 | 1092.00 | 12 : 55 | 23.50 | 10.57 | 45.00 | 0.23 |
| 10th Feb’17 | 189.00 | 420.00 | 3 : 50 | 30.40 | 13.70 | 81.00 | 0.17 |
| 11th Feb’17 | 373.80 | 830.70 | 3 : 40 | 62.90 | 28.32 | 81.00 | 0.35 |
| 17th Feb’17 | 159.60 | 354.70 | 4 :05 | 24.10 | 10.86 | 54.00 | 0.20 |
| 18th Feb’17 | 235.20 | 522.70 | 4: 10 | 34.80 | 15.68 | 54.00 | 0.29 |
| 20th Feb’17 | 247.80 | 550.70 | 5 :30 | 27.80 | 12.52 | 45.00 | 0.28 |
| 22th Feb’17 | 382.20 | 849.30 | 6: 05 | 38.80 | 17.45 | 60.00 | 0.29 |
| 28th Feb'17 | 277.20 | 616.00 | 5: 10 | 33.10 | 14.90 | 63.00 | 0.24 |
| 3rd March'17 | 252.00 | 560.00 | 7: 03 | 22.10 | 9.93 | 39.00 | 0.25 |
| 4th March '17 | 361.20 | 802.70 | 7 : 25 | 30.10 | 13.53 | 93.00 | 0.15 |
| 8th March '17 | 226.80 | 504.00 | 6:00 | 23.30 | 10.50 | 87.00 | 0.12 |
| 9th March '17 | 243.60 | 541.30 | 6 :00 | 25.10 | 11.28 | 72.00 | 0.16 |
| 11th March'17 | 369.60 | 821.30 | 4: 40 | 48.90 | 22.00 | 63.00 | 0.35 |
| 14th March’17 | 491.40 | 1092.00 | 6 : 10 | 49.20 | 22.14 | 60.00 | 0.37 |
| **15th March’17** | **457.80** | **1017.30** | **3: 45** | **75.40** | **33.91** | **75**.00 | **0.45** |
| 20th March’17 | 508.20 | 1129.30 | 5 :50 | 53.80 | 24.20 | 57.00 | 0.42 |
| 22nd March’17 | 554.40 | 1232.00 | 5: 40 | 60.40 | 27.18 | 63.00 | 0.43 |

## 6.3 Effect of Various Parameters on Performance

The system performance is measured in term of COP and SCP. The effect of various parameters on COP and SCP are discussed in following sections.

### 6.3.1 Effect of Hot Water Temperature on COP and SCP

Fig. 6.1 shows the effect of hot water temperature on COP of adsorption chiller. It is observed that the COP is initially increased and then decreases with increase in hot water temperature. It can be seen from the figure that in the range of temperature 60-70 °C, the system has higher COP then all other range of the temperatures. This may be because of, at below 60°C, generator temperature, heat is not sufficient for complete desorption. Subsequently, undesorbed methanol affects next adsorption process which adversely upset the cooling effect. Also, methanol does not reach to condenser pressure after desorption which disturbs the condensation process.

The system required additional time and extra water cycle for same cooling effect results in poor COP. As water temperature increases more than 65°C, the COP decreases. This is because of all the amount of methanol is desorbed and further heat added will not increase the amount of desorbed methanol. Thus the refrigerating effect remains constant. Above 65°C, generator temperature, the overall cycle time is increased due to cool down time of the bed. Such high temperature required more input energy from a source which cannot be satisfied from the conventional solar collector. Even at high temperature, more losses from the system and more fluctuation in water flow for sorption process, which affect the performance of the chiller. Moreover, heat is transferred to connecting devices and tubes which affect the working of condenser and evaporator. Stored heat in bed due to high generator temperature rises the temperature of cold water in the tank due to a cyclic process which affects the absorption process.

In the range of temperature 60-70 °C, higher COP, lower cycle time, lower input energy and higher SCP are observed due to the boiling point of methanol fall under this range. This moderate temperature helps to select, conventional solar water heater system which can operate by FPC or ETC.

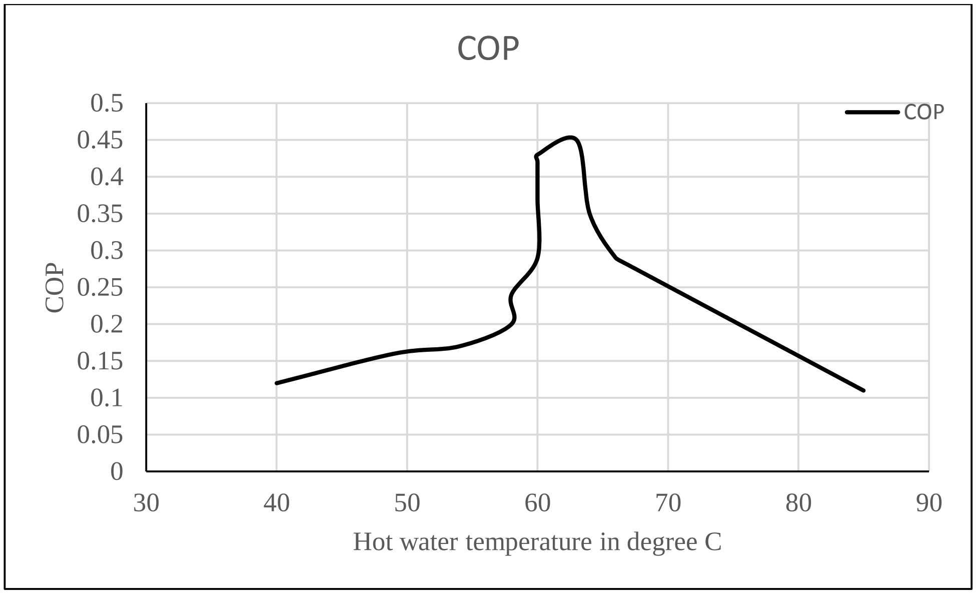


**Figure 6.1 Effect of Hot water temperature on COP**

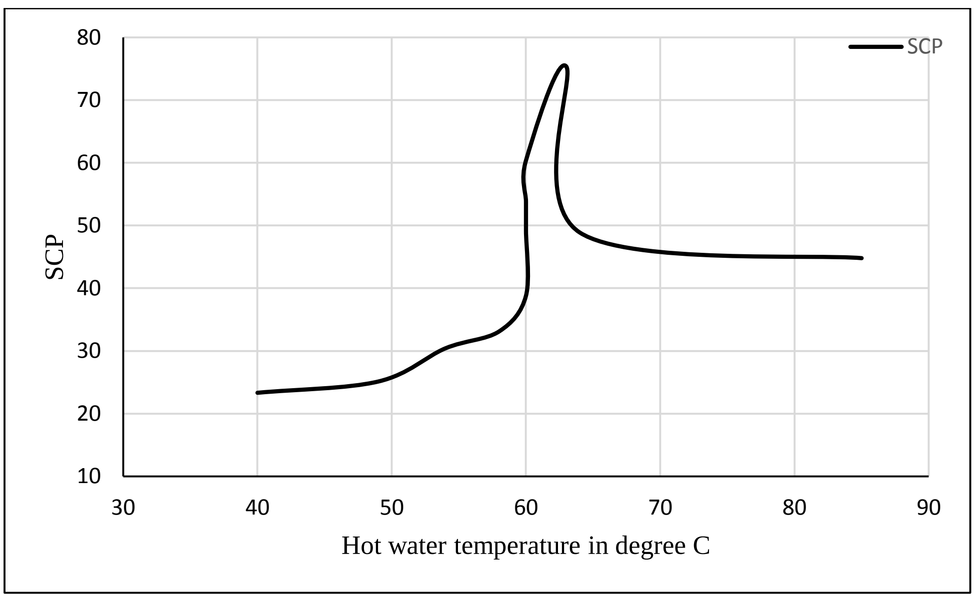


**Figure 6.2 Effect of Hot water temperature on SCP**

The effect of hot water temperature on SCP is shown in Fig. 6.2. It can be seen from the figure that SCP (Cooling effect per unit mass of ACF) is strongly affected by hot water for the fixed mass of ACF.The lower temperature of hot water made the partial desorption with larger cycle time which reduces the cooling effect. The higher temperature of hot water needed more input energy for operation, and it generates higher losses from the system. The hot water temperature at 63°C produces highest SCP (75.4 W/kg) which is due to maximum desorption than SCP is decreased due limiting the capacity of ACF to hold the methanol.

### 6.3.2 Effect of Cold Water Temperature on COP and SCP

Fig. 6.3 and 6.4 show the effect of cold water temperature (i.e. water used to cool the adsorber during adsorption process) on the system COP and SCP respectively. It can be seen from figures that high cold water temperature restricts the movement of methanol from evaporator to adsorber. As a result system pressure rises and saturation temperature of the evaporator will increases. After the cold water temperature of 34°C, the COP and SCP decreased rapidly as the temperature increases. At higher cold water temperature, a smaller amount of methanol being adsorbed and desorbed during each cycle. In the range of 32 to 34°C, cold water temperature, the highest value of COP and SCP is achieved, which help for selecting tap water or natural air as cooling medium for adsorption process.

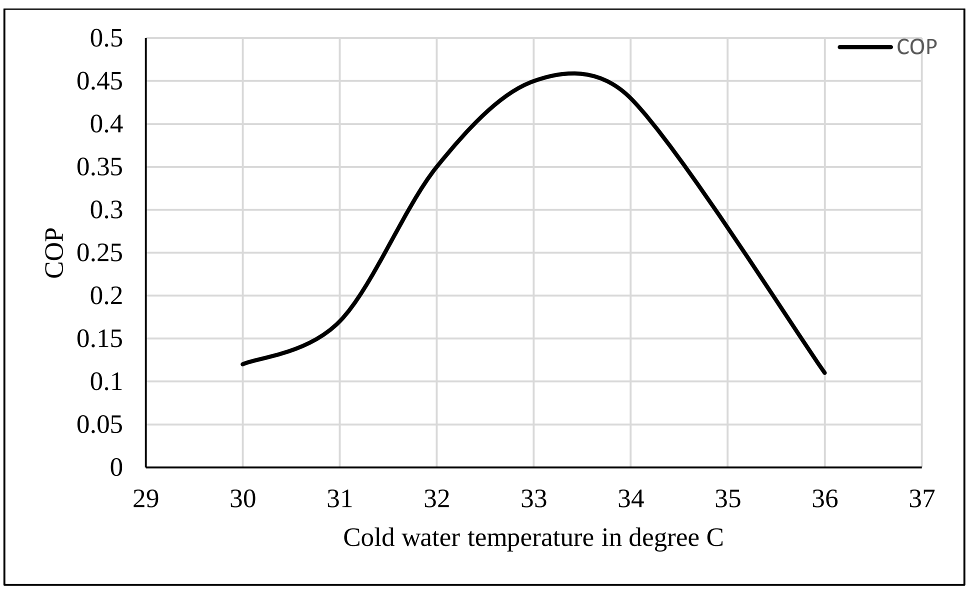


**Figure 6.3 Effect of Cold water temperature on COP**

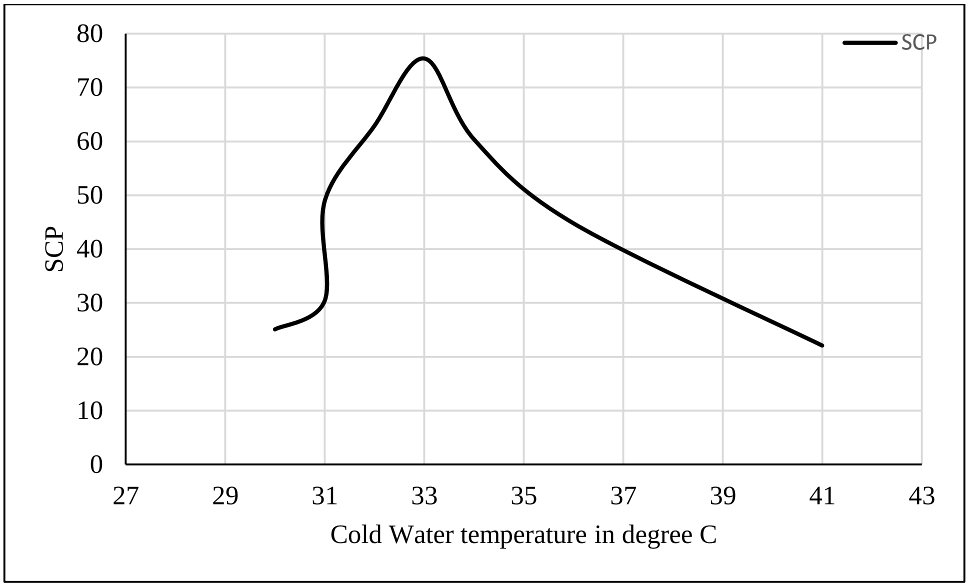


**Figure 6.4 Effect of Cold water temperature on SCP**

### 6.3.3 Effect of Condensing Temperature on COP and SCP

The effect of condensing temperature on the system COP and SCP are shown in Fig. 6.5 and 6.6. It is observed from the figures that, COP and SCP are increased with condensing temperature up to 27 °C & then after decreases trend may be is due to incomplete condensation occurred at a high condensing temperature and which does not allow further methanol from the ACF bed to condenser. The lower condensing temperature obstructs the desorption process and subsequently cooling effect. At high condensing temperature, the amount of condensate methanol decreases and system pressure increases, this lead to reduced cooling effect.

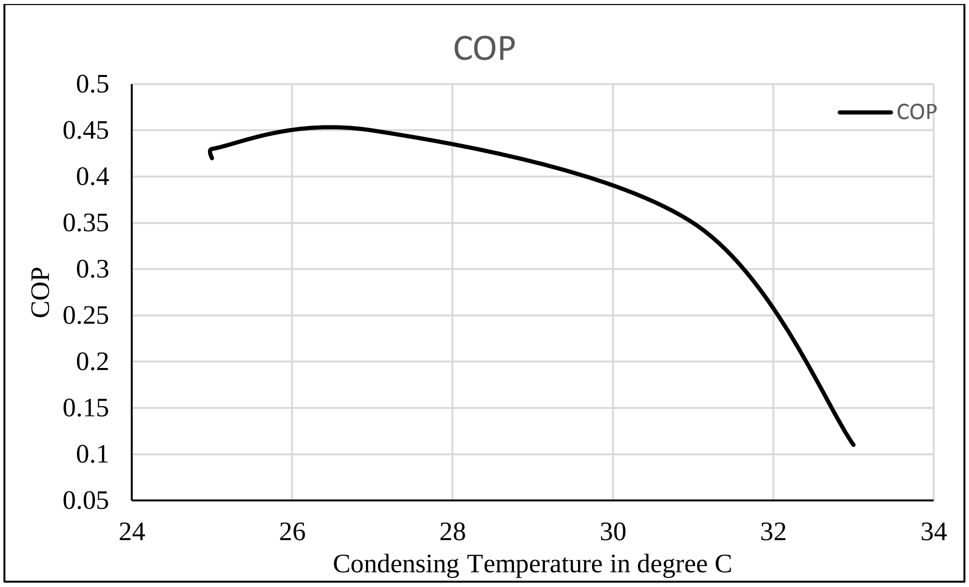


**Figure 6.5 Effect of Condensing temperature on COP**

### 6.3.4 Effect of Evaporator Temperature on COP and SCP

Fig. 6.7 and 6.8 represent the effect of evaporator temperature on COP and SCP. It can be seen from the figures that, the evaporator temperature strongly affect the COP and SCP. The COP and SCP are maximum at 25°C due to less cooling requirement. For lower evaporator temperature, more heat should be rejected from a generator which affects the next desorption cycle, i.e. more heat is required. Also for low evaporating temperature, more energy input and large cycle time is required which in results poor COP and SCP

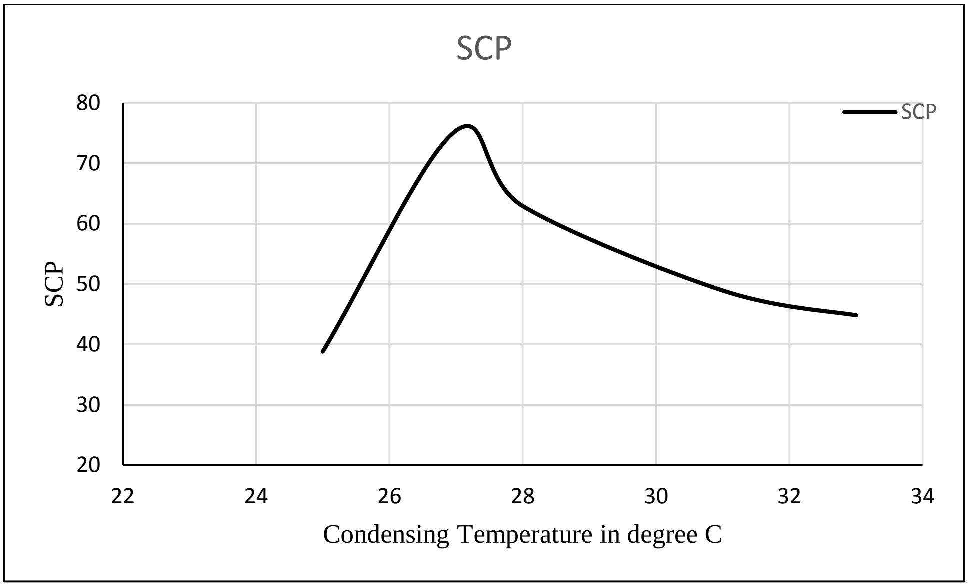


**Figure 6.6 Effect of Condensing temperature on SCP**

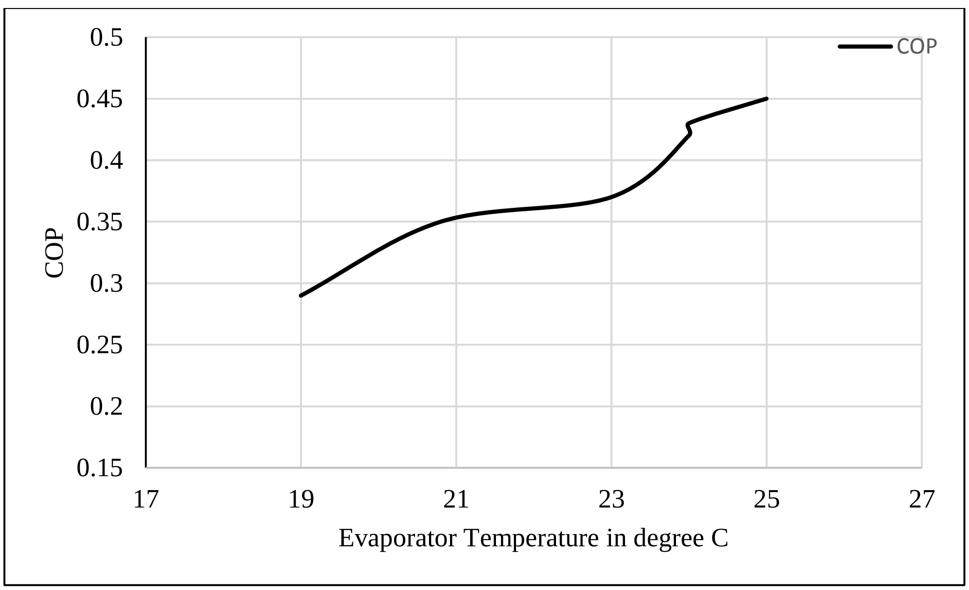


**Figure 6.7 Effect of Evaporator temperature on COP**

### 6.3.5 Effect of Mass Flow Rate of Water *(hot/cold)* and Frequency *(time of hot/cold water)* on COP

The effect of mass flow rate of water and frequency on COP is shown in Fig. 6.9 and 6.10. It can be seen from the figure 6.9 that at 244 kg/hour mass flow rate of hot/cold water, the system achieved the highest COP (0.45). At lower mass flow rate system could not cope up with adsorption and desorption process. Also more cycle time with low cooling effect, which ultimately in poor COP. Higher mass flow rate required more pumping work, which reduces COP by additional energy input to the system. Also, it affects the adsorption process of methanol on to ACF.

It can be observed from Fig. 6.10.1, with 10-minute heating cycle and the 30-minute cooling cycle is given better desorption and adsorption process for system respectively. At lower frequency, there is not enough time for desorption, and at high frequency, poor adsorption occurs. It can be seen from Fig. 6.10.2 , the generator temperature range of 60-65 °C produced higher COP at a frequency of 0.33.

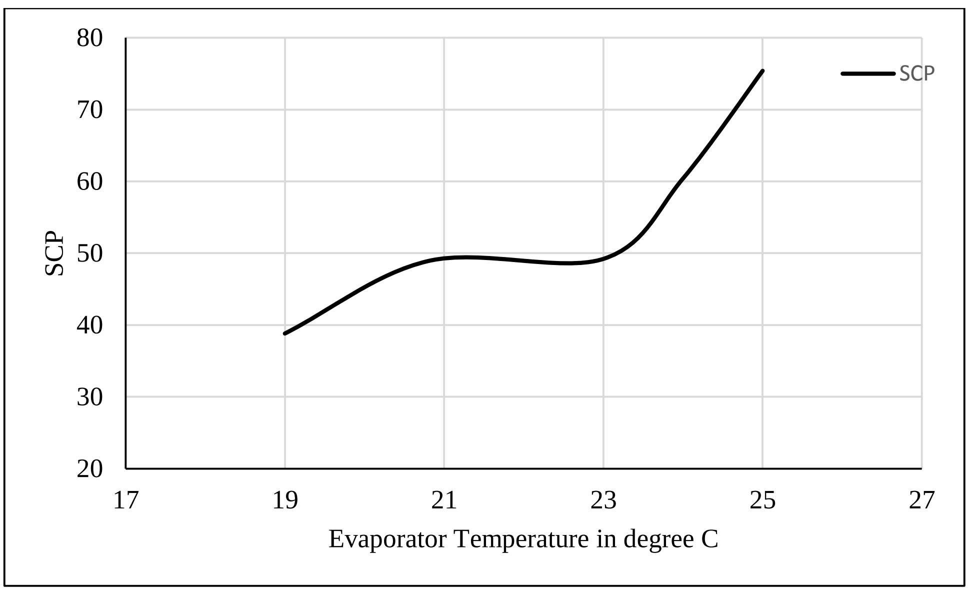


**Figure 6.8 Effect of Evaporator temperature on SCP**

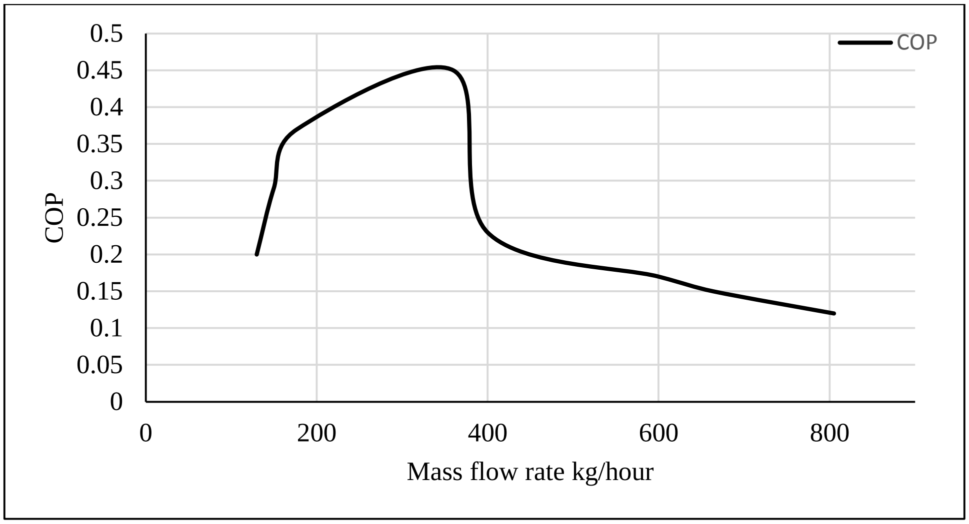


**Figure 6.9 Effect of Mass flow rate of water on COP**

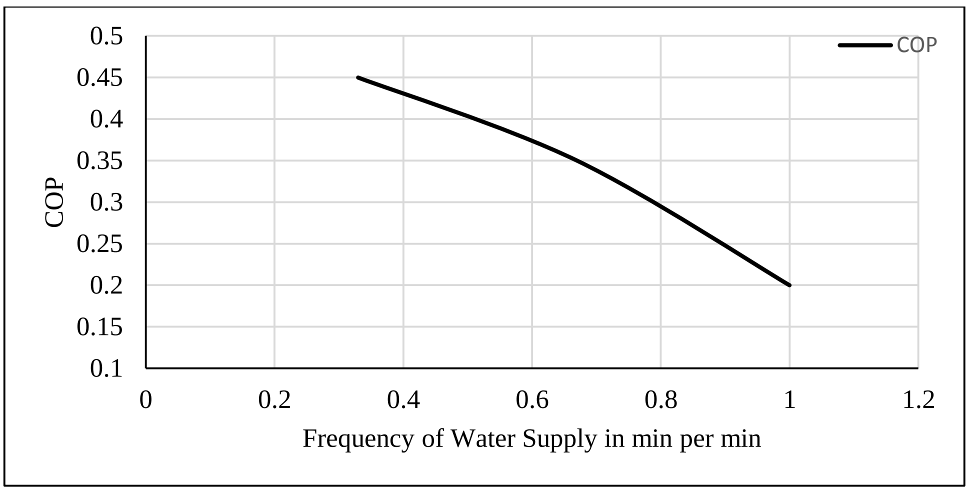


**Figure 6.10.1 Effect of Frequency (time of hot/cold water) of water supply on COP**

### 6.3.6 Effect of Adsorption and Desorption pressure on COP

Adsorption and desorption pressures are system pressure during the process. In the case of adsorption of methanol from the evaporator to ACF bed, the cold water supplied to adsorber bed generates the cooling effect in evaporator and system experienced adsorption pressure or evaporation pressure. Similarly, in desorption process, the system experienced desorption pressure or condensation pressure. High adsorption pressure increases the saturation temperature of the evaporator, which ultimately reduces the COP. Low desorption pressure reduces the saturation temperature of the evaporator and increases specific volume results in the poor cooling effect. Fig. 6.11 and 6.12, shows the effect of Adsorption (Evaporation) pressure and Desorption (Condensation) pressure on COP. It can be seen from the figures, at 244 mm of Hg adsorption pressure and 485 mm of hg desorption pressure, the system gave the highest cop (0.45). It is also concluded from figures that COP is directly influenced by adsorption and desorption pressure.

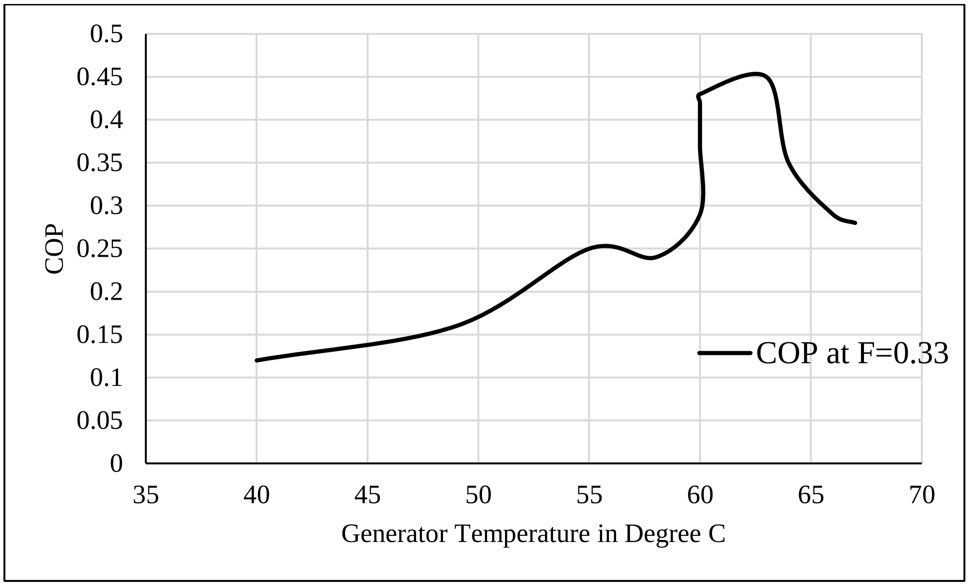


**Figure 6.10.2 Effect of generator temperature on COP at F=0.33**

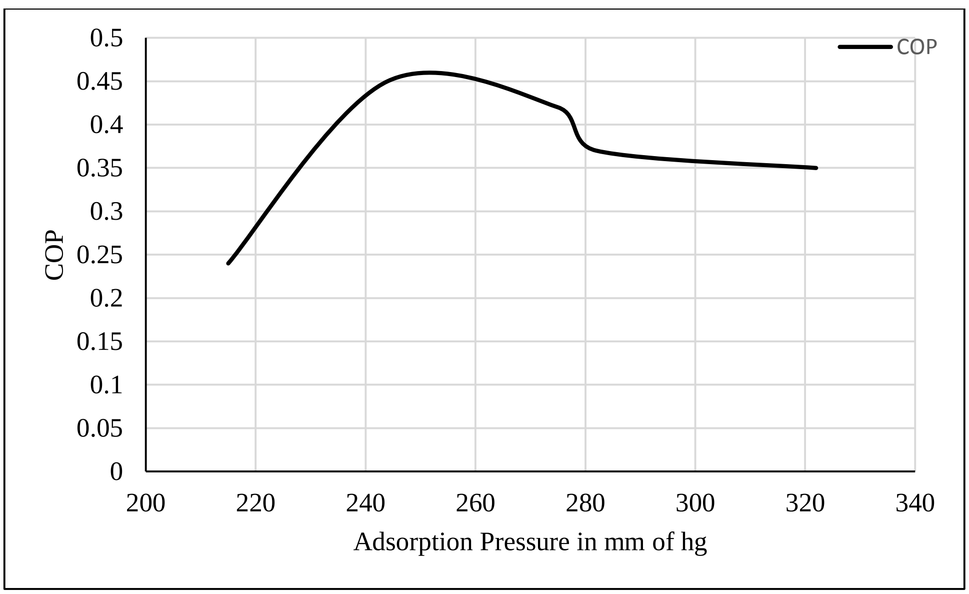


**Figure 6.11 Effect of Adsorption pressure on COP**

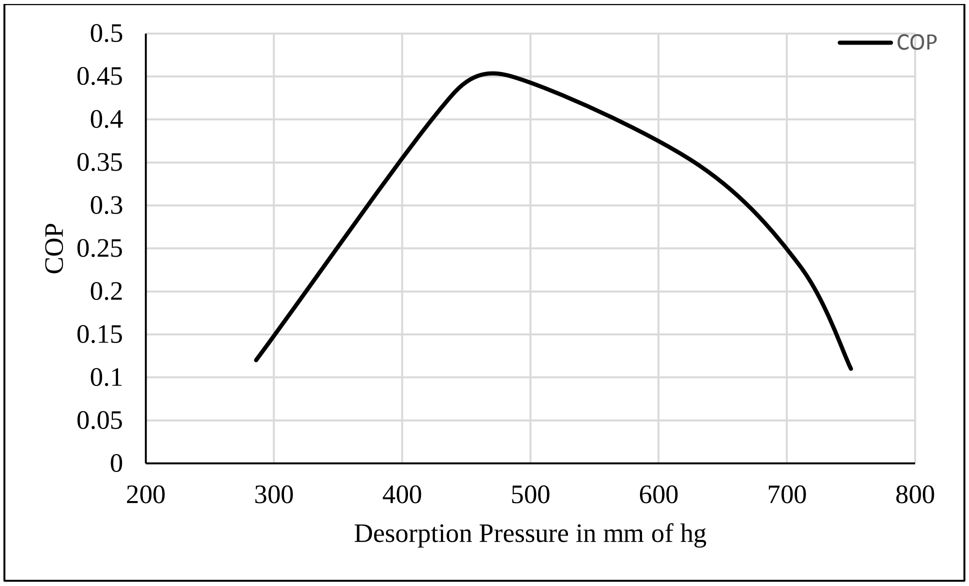


**Figure 6.12 Effect of Desorption pressure on COP**

## 6.4 Day Wise Comparison of Effect Hot Water Temperature on Drop in Evaporator Water Temperature (Cooling Effect)

Fig. 6.13 shows the effect of hot water temperature on a drop in water (Product load) available in the evaporator during experiments performed day wise. It can be seen from the figure that highest (16°C) drop occurs after 80°C, hot water temperature and a small drop in water temperature below 60°C. In addition, it is important to consider total time as well energy input for cooling effect. It is observed that between 60 to 65°C hot water temperatures, the drop in evaporator temperature is sufficient (9 to 10°C) with available total cycle time and input energy to the system. The selection of solar collector is directly affected by the hot water temperature supplied to bed. It is advised to choose hot water temperature of 60-75°C for conventional solar water heater system.

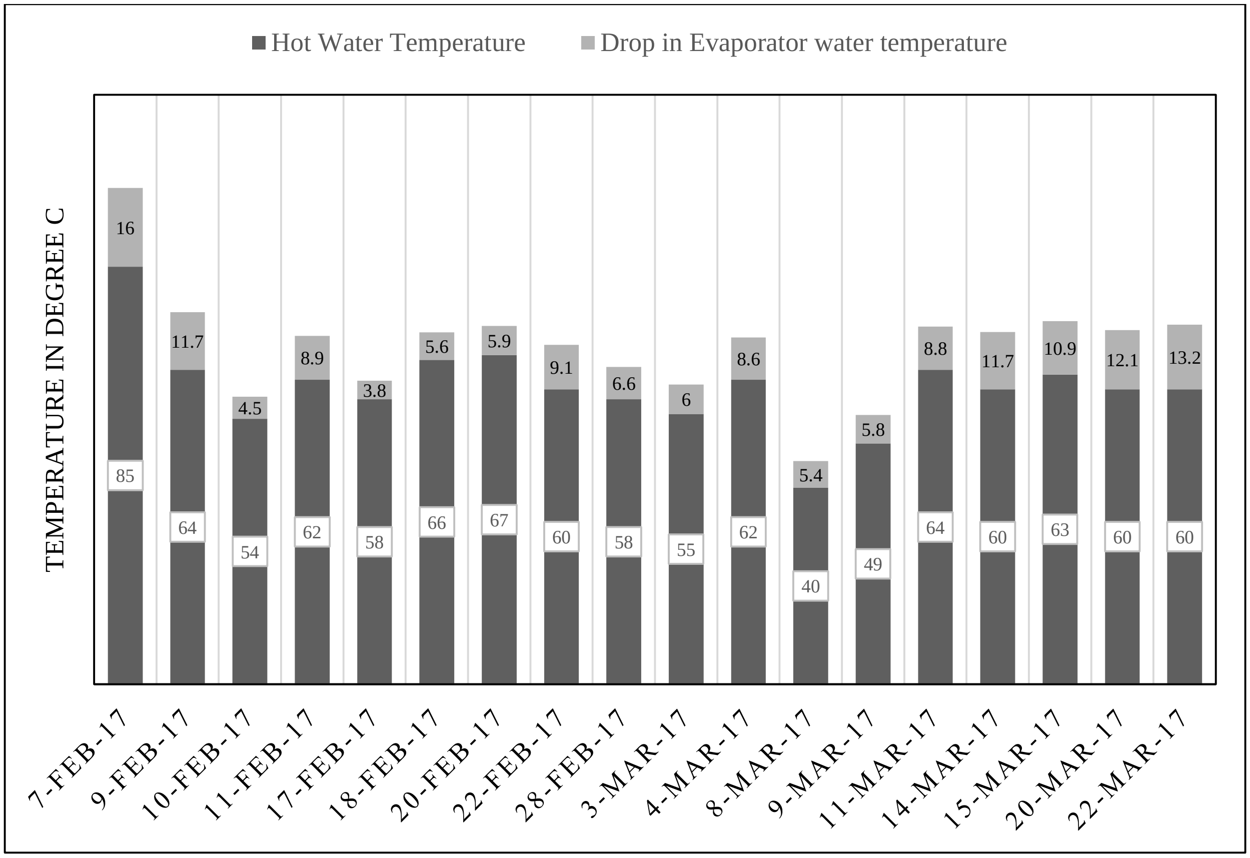


**Figure 6.13 Effect of Hot water temperature on Drop in water temperature (Day Wise)**

## 6.5 Comparison with Intermittent adsorption refrigeration system

The available results from the experimentation are compared with the previous study and presented in Table 6.2. The comparison reveals that proposed adsorption system has lesser cycle time, the low mass of adsorbent and refrigerant for higher SCP and COP. Even generation temperature is less which helps to select low power heat source and conventional solar collector for this chiller. By maintaining moderate adsorption temperature (Atmospheric air or tap water), the proposed system produced desire cooling effect. This adsorption chiller is better due to working pair, design and optimization in working parameters like temperature, pressure, time. This system is designed and developed for water chiller (8-10°C drop in water temperature) operated by FPC or ETC based solar water heater for achieving dual advantages of the water heater and refrigeration system.

**Table 6.2 Comparison with Intermittent System**

| **Parameter/ Author** | ***Boubakri [50]*** | ***González et.al.[51]*** | Hassan ***[54]*** | ***Wang et.al. [4]*** | ***Pons and Guilleminot [52]*** | ***Suleiman et.al.[53]*** | ***Wang et.al. [25]*** | ***Anyanwu and Ogueke [40]*** | ***Bhargav. et al.*** |
|---|---|---|---|---|---|---|---|---|---|
| ***Product Load*** | 5.2 kg of Ice/day | 2.2 MJ/ sqm. Per day | 12.15 MJ per cycle | 8 kg of Ice/day | 30kg of Ice/day | 4814.83 KJ | 10kg of Ice/day | 3 kg of Ice/day | 10° C drop in 10 kg of water |
| ***Cooling Effect ( KJ)*** | 2392 | 2200 | 12150 | 3680 | 13800 | 4814.83 | 4600 | 1380 | 458 |
| ***Cooling Effect ( W)*** | 27.68 | 25.46 | 143.75 | 42.59 | 159.72 | 55.73 | 53.24 | 15.97 | 33.91 |
| ***Generation Temp.(° C)*** | 95 | 120 | 120 | 120 | 100-110 | 80 | 98 | 100 | 63 |
| ***Adsorption Temp. (° C)*** | 22 | 18 | 30 | 30 | 25 | 25 | 20 | 20 | 33 |
| ***Cycle Time ( hour)*** | 24 | 24 | 24 | 24 | 24 | - | 24 | 20 | 3 hours, 45 minutes |
| ***Condenser Temp. (° C)*** | 20 | - | 35 | 40 | 25-40 | 25 | 30 | 35 | 27 |
| ***Evaporator Temp. (° C)*** | -10 | 0.7 | -5 | -10 | -3 | 0 | -2 | -10 | 19.4 |
| ***COP*** | 0.14 | 0.086 | 0.616 | 0.55 | 0.12 | 0.608 | 0.067 | 0.015 | 0.45 |
| ***SCP ( W/kg)*** | 1.384 | 3.53 | 3.19 | 85.18 | 1.22 | 2.13 | 1.9 | 1.9 | 75.4 |
| ***Mass of AC (kg)*** | 20 | 7.2 | 45 | 0.5 kg ACF | 130 | 26.07 | 28 | 8.4 | 0.45 kg ACF |
| ***Mass of Methanol(kg)*** | - | 2.2 | 10.79 | - | - | 8.1 | 8 | - | 0.65 |
| ***Collector*** | FPC – 1 sqm. | CPC - 0.55 Aperture Area | - | - | FPC – 6 sqm | FPC – 2 sqm | Heat pipe ETC – 2 sqm | FPC – 1.2 sqm | Hot Water Tank with Electrical Heater |

# CHAPTER 7

# Conclusion

The solar-powered adsorption refrigeration system is undoubtedly a better option than a conventional chiller because of its eco-friendly nature, low cost and simplicity. The objective of the study is to develop adsorption water chiller powered by the residential solar water heater and to select best working environment for it. Many places in India as well another part of the world are still cut off from the electrical grid, and even there is a requirement of the cooling system for different applications. The proposed system can satisfy the requirement of water chiller which can be used for food and medicine preservation and many more such applications. Intermittent and Continuous adsorption refrigeration systems have already investigated and reported but needs more attention. ACF-Methanol based semi-continuous system operates at a low generator temperature which can be easily achieved by FPC/ETC based solar water heater. Detailed investigation of adsorption capacity, hybrid adsorption refrigeration system and working environment were conducted by the scientific and engineering approach. The adsorption capacity of ACF-methanol pair is obtained by isobaric adsorption method, and it correlates with Dubinin-Astakhov equation.

The test facility is designed and fabricated to attain 10 to 15°C drop in water temperature which can be used as water chiller for food preservation. The drop in evaporator temperature of 10.9° C is achieved by the flow rate of water as 360 kg/hour, and at a condenser temperature of 27°C, It is observed that the pressure oscillation between 244 mm of Hg. (33 kPa) to 485 mm of Hg. (65 kPa) during investigation due to desorption and adsorption phenomenon in the test set up. The total time observed is 4 hours for 457 kJ cooling effect, which can be reduced by maintaining the flow rate of water. The overall cycle time is found very less compared to intermittent cycle (4 hours vs 24 hours). The range of various system parameters pertaining to a higher range of COP and SCP are mentioned in below table.

| Performance parameter | System parameter | Range of system parameter |
|---|---|---|
| COP | Hot water temperature | 55-65 °C |
| | Cold water temperature | 32-35 °C |
| | Condenser temperature | 26-30 °C |
| | Evaporator temperature | 21-25 °C |
| | Flow rate of water | 200-400 kg/hour |
| | Frequency of water supply | 0.3 -0.5 |
| SCP | Hot water temperature | 55-65 °C |
| | Cold water temperature | 32-35 °C |
| | Condenser temperature | 26-30 °C |
| | Evaporator temperature | 21-25 °C |

Following conclusions are drawn from the present study:

1. The maximum adsorption capacity found is 0.44 kg/kg for ACF-methanol pair on the test set up.
2. The highest value of COP (0.45) and SCP (75.4 W/kg) is achieved at a hot water temperature of 63°C, a cold water temperature of 33°C and a condenser temperature of 27 °C in suggested adsorption refrigeration system.
3. The lower mass of ACF (450 gram) and methanol (650 ml) required the smaller size of adsorber, evaporator, condenser and connecting copper tube.
4. The difficulties found during development and experimentation are mounting of ACF on copper tubes, the requirement of vacuum, charging of methanol, the flow rate of water, optimization of cycle time, the effect of environment, the response of measuring instruments and periodic observation of parameter.

## Limitations

1. It was presumed that existing solar water heater could power the proposed chiller and the movement of heat transfer fluid (hot/cold water) occurred due to density gradient. Nevertheless, little pump work is required to maintain the flow rate of water for desired cooling effect.

2. For better results, suggested hot water temperature for desorption is above 50° C in present chiller because of methanol flash point.
3. The performance of adsorption water chiller will slow down after some years (7 to 8) because of degradation in adsorptive properties of ACF, hence ACF needs to be replaced from adsorber bed in the period of time.

**Recommendations**

1. The system performance can be improved by the data logger and electronic controller (water flow rate, cycle frequency etc.).
2. Overall cycle time for refrigeration can be reduced by appropriate generator temperature and flow rate of water.
3. For better performance, keep flowing water in condenser and evaporator rather than keeping it steady.

**Scope of Further Work**

1. The real Solar collector can be attached to the system and investigate the same setup.
2. With two beds arrangement, the system performance can be improved, and continuous cooling can be achieved
3. By improving Adsorption properties of ACF, system can give higher adsorption capacity which will result in compact size and better performance
4. The system can also be designed with heat available from Biomass and waste heat.

From the obtained results it is concluded that hybridizing of the solar water heater with adsorption refrigerator can satisfy water heating and food preservation requirement. The working environment in term of the temperature of hot water & cold water, the flow rate of water and temperature of the condenser can easily manage with available resources for the production of cooling effect through the developed chiller. This chiller is expected to be reasonable in INDIA in upcoming time for short-term storage of food at the farm. The present system can achieve high SCP at low generation temperature by adsorptive properties of working pair and efficient design of chiller. The off-site observation and control can be possible by proper electronic instrument and software with the system.

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# Appendix A

## Activated Carbon Fiber & Methanol Data Sheet

1. **ACF Sample Supplier: ENVIRON CARE PRODUCTS,** E-1, Site-B, Surajpur Industrial Area,Greater Noida (UP) – 201308(India)

**Properties of ACF :**

| | | |
|---|---|---|
| 1 | Moisture Content | 1.76-2.73 % |
| 2 | Ash Content | <2.65 % |
| 3 | Carbon Content | 97.35 % |
| 4 | Surface Area | 1200-1700 m /g |
| 5 | pH | 3.45-3.6 |
| 6 | Iodine Adsorption Number | 1250-1750 (mg/gm) |
| 7 | Pore Size | 16.87 $A^0$ |
| 8 | Density | 0.444 (g / cc) |
| 9 | Decomposition temperature | 5500 °C |

**Adsorption Properties of ACF :**

| | | |
|---|---|---|
| 1 | Ni Metal Ions | 26-28% |
| 2 | Pb Ions | 40-42% |
| 3 | Copper Ions | 15-17% |
| 4 | Zinc Ions | 14-16% |
| 5 | Chromium (IV) | 97-99% with 5000 micro gm |
| 6 | Sulphur dioxide | 85-88% with 30 ppm |
| 7 | Hydrogen Sulphide | 86-88% with 30 ppm |
| 8 | Acid Vapours (HCl) | 51-53% |
| 9 | Organic Vapours / Solvents | 88 to 95 % for Benzene, CTC, Hexane, Toluene etc. |
| 10 | Carbon Monoxide | 32-34%(ACF treated with CuCl & noble metals is expected to show better results) |
| 11 | Ammonia | Upto 61% with 1% aqueous solution |

2. **Methanol Supplier:** S.D. Fine Chem ltd., Mumbai (Batch N0- F13A/0913/2905/13, 99% Methanol**)**

**Properties of Methanol :**

| | | |
|---|---|---|
| 1 | Boiling Point | 64.7ºC |
| 2 | Density | 0.791 g/mL at 25ºC |
| 3 | Melting Point | -98ºC |
| 4 | Viscosity (cP) | 0.544 at 25ºC |
| 5 | Thermal Conductivity | 200 mW $m^{-1}$ $K^{-1}$ at 25ºC |

# Appendix B: Experimental Data

**Date: 07.02/2017**

| TIME | Cycle | Pressure | Flow Rate | Temperature of Hot Water (Degree C) | | TH | Temperature of cold Water (Degree C) | | TC | Temp. of Water at Entry & Exit of Bed (Degree C) | | Condenser Temp. (Degree C) | | | Evaporator Temp. (Degree C) | | | Bed |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | (heating/Cooling) | (mm of Hg) | (kg/ hour) | | | | | | | | | Water | Meth_ in | Meth_ out | Water | Meth _in | Meth_ out | Meth_ in |
| | | | | Tw | T12 | | Tt | T11 | | T21 | T13 | T28 | T22 | T26 | T27 | T25 | T24 | T23 |
| 10.20 | H | 700 | 614 | 80 | 82 | 81 | 48 | 51 | 50 | 33 | 31 | 32 | 37 | 33 | 33 | 33 | 34 | 34 |
| 10.45 | | 650 | 494 | 84 | 87 | 85 | 48 | 52 | 50 | 34 | 32 | 34 | 38 | 35 | 34 | 36 | 38 | 37 |
| 11 | | 10 | | 81 | 84 | 82 | 48 | 51 | 50 | 0 | 90 | 35 | 33 | 31 | 25 | 26 | 17 | 20 |
| 11.05 | | 0 | 538 | 82 | 86 | 84 | 49 | 53 | 51 | 0 | 90 | 36 | 37 | 36 | 27 | 30 | 32 | 26 |
| 11.2 | | 5 | | 85 | 88 | 87 | 38 | 39 | 38 | 5 | 73 | 37 | 37 | 38 | 29 | 33 | 36 | 31 |
| 11.3 | C | 100 | | 85 | 88 | 86 | 29 | 33 | 31 | 15 | 60 | 38 | 37 | 38 | 31 | 34 | 37 | 33 |
| 11.4 | | 150 | 695 | 85 | 87 | 86 | 29 | 33 | 31 | 19 | 54 | 39 | 37 | 38 | 32 | 35 | 38 | 34 |
| 11.5 | | 540 | 656 | 85 | 87 | 86 | 32 | 35 | 34 | 38 | 37 | 39 | 37 | 39 | 33 | 37 | 40 | 37 |
| 11.55 | | 540 | 645 | 85 | 86 | 86 | 32 | 36 | 34 | 36 | 36 | 39 | 38 | 39 | 33 | 37 | 40 | 39 |
| 12.05 | | 540 | | 85 | 86 | 86 | 33 | 35 | 34 | 34 | 37 | 40 | 38 | 39 | 34 | 37 | 41 | 39 |
| 12.13 | | 540 | | 85 | 87 | 86 | 33 | 35 | 34 | 34 | 37 | 40 | 39 | 40 | 35 | 38 | 41 | 40 |
| 12.3 | | 535 | | 85 | 86 | 85 | 34 | 36 | 35 | 33 | 38 | 41 | 39 | 41 | 36 | 38 | 43 | 40 |
| 12.35 | | 5 | 575 | 80 | 81 | 80 | 34 | 36 | 35 | 0 | 86 | 41 | 19 | 35 | 31 | 30 | 23 | 24 |
| 12.45 | H | 5 | | 81 | 83 | 82 | 34 | 36 | 35 | 0 | 86 | 42 | 31 | 40 | 33 | 34 | 37 | 30 |
| 12.55 | | 5 | 548 | 83 | 85 | 84 | 34 | 37 | 35 | 0 | 88 | 42 | 37 | 43 | 34 | 36 | 40 | 34 |
| 2.1 | | 501 | | 85 | 88 | 87 | 38 | 41 | 39 | 38 | 42 | 34 | 39 | 42 | **40** | 39 | 43 | 41 |
| 2.2 | C | 500 | | 85 | 88 | 86 | 38 | 41 | 39 | 39 | 42 | 33 | 38 | 41 | 39 | 38 | 42 | 40 |
| 2.3 | | 520 | | 84 | 85 | 84 | 30 | 31 | 30 | 30 | 36 | 24 | 31 | 29 | 27 | 28 | 39 | 28 |
| 2.45 | | 545 | 732 | 84 | 84 | 84 | 31 | 31 | 31 | 27 | 33 | 24 | 30 | 30 | 28 | 28 | 31 | 29 |
| 3 | | 545 | 743 | 84 | 85 | 84 | 31 | 32 | 31 | 28 | 34 | 25 | 30 | 30 | 27 | 29 | 32 | 30 |
| 3.13 | | 545 | 322 | 85 | 87 | 86 | 33 | 34 | 33 | 30 | 36 | 25 | 30 | 31 | 24 | 29 | 33 | 31 |
| 3.50 pm | | 545 | 304 | 85 | 86 | 86 | 33 | 34 | 34 | 29 | 36 | 25 | 30 | 30 | 24 | 29 | 33 | 31 |
| 4.1 | H | 0 | | 82 | 84 | 83 | 33 | 35 | 34 | 75 | 87 | 28 | 19 | 29 | 24 | 24 | 28 | 22 |
| 4.2 | | 0 | | 84 | 86 | 85 | 33 | 36 | 34 | 76 | 89 | 28 | 29 | 32 | 24 | 26 | 30 | 26 |
| 4.3 | | 0 | | 85 | 88 | 87 | 33 | 36 | 34 | 76 | 89 | 28 | 29 | 32 | **24** | 27 | 31 | 26 |
| 4.4 | C | 515 | 376 | 85 | 87 | 86 | 36 | 39 | 37 | 27 | 40 | 28 | 30 | 31 | 25 | 29 | 34 | 31 |
| 4.5 | | 515 | | 85 | 87 | 86 | 36 | 39 | 37 | 29 | 40 | 28 | 30 | 31 | 25 | 29 | 33 | 31 |
| 5 | | 515 | | 85 | 86 | 86 | 37 | 39 | 38 | 32 | 41 | 29 | 30 | 30 | 25 | 29 | 33 | 31 |
| 6.3 | | 545 | 248 | 85 | 85 | 85 | 30 | 31 | 31 | 30 | 34 | 30 | 31 | 28 | 26 | 28 | 30 | 29 |
| 6.4 | | 545 | 227 | 85 | 85 | 85 | 30 | 32 | 31 | 32 | 35 | 31 | 31 | 29 | 27 | 29 | 31 | 30 |
| 7 | | 545 | 213 | 85 | 86 | 85 | 29 | 32 | 31 | 33 | 35 | 31 | 31 | 29 | 28 | 29 | 32 | 31 |
| 7.15 | | 556 | 790 | 85 | 86 | 86 | 30 | 33 | 32 | 34 | 36 | 31 | 31 | 29 | 28 | 29 | 32 | 31 |
| 7.25 | | 556 | | 85 | 86 | 86 | 30 | 34 | 32 | 32 | 36 | 31 | 31 | 29 | 29 | 30 | 31,7 | 31 |
| 7.35 | | 556 | 590 | 85 | 86 | 86 | 30 | 33 | 31 | 33 | 36 | 31 | 31 | 29 | 29 | 30 | 32 | 31 |

**Date: 09/02/2017**

| TIME | Cycle | Pressure | Flow Rate | Temperature of Hot Water (Degree C) | | TH | Temperature of cold Water (Degree C) | | TC | Temp. of Water at Entry & Exit of Bed (Degree C) | | Condenser Temp. (Degree C) | | | Evaporator Temp. (Degree C) | | | Bed |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | (heating/Cooling) | (mm of Hg) | (kg/hour) | | | | | | | | | Water | Meth_in | Meth_out | Water | Meth_in | Meth_out | Meth_in |
| | | | | Tw | T12 | | Tt | T11 | | T21 | T13 | T28 | T22 | T26 | T27 | T25 | T24 | T23 |
| 9.00 am | H | 610 | | 74 | 73.1 | 73.6 | 29 | 28.8 | 29 | 29 | 22.7 | 30 | 36.5 | 25.2 | 29.9 | 28.5 | 25.2 | 26.5 |
| 9.3 | H | 610 | 340 | 73 | 69.9 | 71.5 | 28 | 29.6 | 29 | 79.2 | 42.3 | 30.8 | 38 | 31.3 | 34.9 | 31 | 30.6 | 31.1 |
| 9.45 | H | 50 | 100 | 67 | 66.6 | 66.8 | 28 | 30.3 | 29 | 74..1 | 71.3 | 31.6 | 38 | 34.8 | 26.2 | 30.9 | 30.8 | 28.2 |
| 10 | H | 50 | | 66 | 66.7 | 66.4 | 28 | 30.4 | 29 | 70 | 69.2 | 33.2 | 38.7 | 36.4 | 29 | 32.6 | 32.9 | 29.7 |
| 10.15 | H | 55 | 516 | 66 | 66.7 | 66.4 | 28 | 30.1 | 29 | 68.9 | 68.5 | 32.3 | 38.7 | 37.3 | 30.3 | 33.43 | 33.7 | 30.6 |
| 10.3 | C | 545 | | 66 | 66.8 | 66.4 | 28 | 30.2 | 29 | 31 | 30 | 32.3 | 39.9 | 38.8 | 32.3 | 35.7 | 36.9 | 34.9 |
| 6.45 pm | C | 545 | | 63 | 62.8 | 62.9 | 29 | 29.9 | 29 | 28.7 | 31 | 26.1 | 34.3 | 27.1 | 26.6 | 28.2 | 27.3 | 27.3 |
| 6.55 | C | 545 | | 63 | 62.5 | 62.8 | 28 | 29 | 29 | 28.8 | 30.6 | 26.5 | 32.8 | 27.7 | 26.5 | 27.8 | 28.4 | 28.2 |
| 7.15 | C | 545 | 118 | 63 | 64.5 | 63.8 | 28 | 30.4 | 29 | 31.2 | 32.7 | 27.1 | 32.8 | 29.1 | 26.5 | 28.7 | 30.2 | 29.6 |
| 7.25 | C | 545 | | 63 | 64.5 | 63.8 | 29 | 31.3 | 30 | 32.8 | 33.1 | 27.6 | 33 | 29.6 | 26.3 | 29.3 | 31.1 | 30.3 |
| 7.35 | C | 545 | 752 | 63 | 64.3 | 63.7 | 30 | 32.5 | 31 | 32.7 | 34.6 | 27.7 | 33.1 | 30 | 26.3 | 29.7 | 31.4 | 30.7 |
| 7.45 | C | 545 | | 62 | 64.7 | 63.4 | 29 | 32.4 | 31 | 32.5 | 34.7 | 27.9 | 33.4 | 30.4 | 25.9 | 29.8 | 31.6 | 31 |
| 7.55 | C | 545 | | 62 | 64.9 | 63.5 | 30 | 32.5 | 31 | 33.5 | 35.4 | 27.8 | 33.5 | 30.3 | 25.8 | 30 | 31.7 | 31.1 |
| 8.05 | C | 545 | 447 | 62 | 65 | 63.5 | 29 | 32.9 | 31 | 33.6 | 35.9 | 27.7 | 34 | 30.6 | 25.2 | 29.9 | 31.9 | 31.3 |
| 8.15 | C | 545 | | 62 | 64.6 | 63.3 | 29 | 33 | 31 | 33.7 | 36 | 27.7 | 33.7 | 30.7 | 24.9 | 29.9 | 31.8 | 31.3 |
| 8.25 | C | 545 | 447 | 62 | 64.6 | 63.3 | 30 | 33.5 | 32 | 33.8 | 36 | 27.7 | 33.7 | 30.4 | 24.7 | 29.8 | 31.9 | 31.1 |
| 8.35 | C | 545 | | 62 | 64.6 | 63.3 | 30 | 33.3 | 32 | 33.9 | 36.1 | 27.4 | 33.7 | 30.5 | 24.6 | 29.8 | 31.5 | 31 |
| 8.45 | C | 545 | 444 | 62 | 64.7 | 63.4 | 30 | 33.3 | 32 | 34 | 36.2 | 27.6 | 33.7 | 30.5 | 24.3 | 29.8 | 31.8 | 31.1 |
| 8.55 | C | 545 | | 62 | 64.3 | 63.2 | 30 | 33.3 | 32 | 34.1 | 36.3 | 27.3 | 33.8 | 30.4 | 23.8 | 29.5 | 31.2 | 30.8 |
| 9.05 | C | 545 | | 62 | 64.6 | 63.3 | 30 | 33.3 | 32 | 34.1 | 36.2 | 27.2 | 33.8 | 30.1 | 23.7 | 29.5 | 31.4 | 30.7 |
| 9.15 | C | 545 | 363 | 62 | 64.5 | 63.3 | 29 | 33.2 | 31 | 33.4 | 36.6 | 26.9 | 33.6 | 30 | 23.2 | 29.2 | 30.8 | 30.5 |
| 9.35 | C | 310 | 650 | 58 | 60.2 | 59.1 | 29 | 33 | 31 | 61.6 | 64 | 27.1 | 33.6 | 30.1 | 23.2 | 28.3 | 29.6 | 28.7 |
| 9.45 | C | 255 | 590 | 58 | 60.3 | 59.2 | 29 | 32.7 | 31 | 59.1 | 63.4 | 27.1 | 33.4 | 30.5 | 23.2 | 28.3 | 29.8 | 27.7 |
| 9.55 | C | 255 | 640 | 57 | 60.1 | 58.6 | 29 | 32.7 | 31 | 58.3 | 62.4 | 27.1 | 33.4 | 30.7 | 23.3 | 28.2 | 29.9 | 28.2 |

**Date:10/02/2017**

| TIME | Cycle (heating/Cooling) | Pressure (mm of Hg) | Flow Rate (kg/hour) | Temperature of Hot Water (Degree C) | | TH | Temperature of cold Water (Degree C) | | TC | Temp. of Water at Entry & Exit of Bed (Degree C) | | Condenser Temp. (Degree C) | | | Evaporator Temp. (Degree C) | | | Bed |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | Water | Meth_in | Meth_out | Water | Meth_in | Meth_out | Meth_in |
| | | | | Tw | T12 | | Tt | T11 | | T21 | T13 | T28 | T22 | T26 | T27 | T25 | T24 | T23 |
| 6.40 pm | H | 530 | | 47 | 49 | 48 | 29 | 29 | 29 | 28 | 31 | 26 | 34 | 27 | 29 | 28 | 27 | 27 |
| 6.5 | | 400 | | 47 | 50 | 48 | 29 | 29 | 29 | 49 | 51 | 27 | 33 | 28 | 29 | 27 | 28 | 26 |
| 7 | | 365 | | 50 | 53 | 51 | 29 | 31 | 30 | 51 | 54 | 28 | 32 | 29 | 29 | 28 | 29 | 26 |
| 7.15 | C | 530 | 157 | 53 | 57 | 55 | 30 | 33 | 31 | 30 | 35 | 27 | 32 | 29 | 28 | 28 | 30 | 28 |
| 7.2 | | 530 | 108 | 55 | 60 | 57 | 30 | 33 | 32 | 31 | 36 | 28 | 32 | 29 | 28 | 28 | 30 | 29 |
| 7.25 | | 530 | | 56 | 61 | 58 | 30 | 34 | 32 | 31 | 36 | 28 | 32 | 29 | 28 | 29 | 31 | 29 |
| 7.3 | H | 370 | | 55 | 60 | 58 | 31 | 35 | 33 | 56 | 57 | 28 | 29 | 26 | 28 | 23 | 18 | 20 |
| 7.35 | | 300 | | 56 | 61 | 58 | 31 | 35 | 33 | 56 | 60 | 28 | 30 | 27 | 27 | 24 | 20 | 20 |
| 7.45 | C | 510 | 113 | 58 | 63 | 61 | 31 | 35 | 33 | 30 | 38 | 28 | 32 | 29 | 27 | 28 | 29 | 28 |
| 7.55 | | 510 | 133 | 61 | 66 | 64 | 31 | 35 | 33 | 31 | 37 | 28 | 32 | 29 | 27 | 29 | 31 | 29 |
| 8.05 | | 510 | | 64 | 68 | 66 | 30 | 35 | 32 | 31 | 38 | 28 | 33 | 29 | 27 | 29 | 31 | 30 |
| 8.1 | H | 300 | 138 | 61 | 67 | 64 | 30 | 35 | 32 | 62 | 64 | 28 | 29 | 26 | 25 | 23 | 17 | 19 |
| 8.15 | | 160 | | 62 | 69 | 65 | 30 | 35 | 32 | 63 | 68 | 28 | 30 | 28 | 25 | 24 | 22 | 20 |
| 8.2 | C | 510 | 114 | 63 | 69 | 66 | 30 | 35 | 32 | 30 | 52 | 29 | 32 | 29 | 25 | 27 | 27 | 25 |
| 8.3 | | 520 | 112 | 65 | 70 | 68 | 30 | 35 | 32 | 93 | 37 | 29 | 32 | 29 | 25 | 28 | 30 | 28 |
| 8.4 | | 520 | | 65 | 70.O | 65 | 31 | 35 | 33 | 31 | 37 | 29 | 32 | 29 | 25 | 29 | 31 | 30 |
| 8.45 | H | 300 | 160 | 62 | 67 | 65 | 31 | 35 | 33 | 63 | 64 | 29 | 29 | 26 | 25 | 23 | 17 | 18 |
| 8.55 | | 100 | | 64 | 70 | 67 | 31 | 35 | 33 | 65 | 70 | 29 | 32 | 29 | 24 | 25 | 26 | 23 |
| 9.1 | C | 510 | 77 | 65 | 69 | 67 | 30 | 34 | 32 | 30 | 37 | 29 | 33 | 29 | 24 | 28 | 30 | 28 |
| 9.2 | | 520 | 110 | 65 | 69 | 67 | 30 | 34 | 32 | 31 | 36 | 29 | 33 | 29 | 24 | 28 | 30 | 29 |
| 9.3 | | 520 | | 65 | 69 | 67 | 30 | 34 | 32 | 32 | 30 | 29 | 33 | 29 | 24 | 28 | 30 | 30 |
| 9.35 | H | 170 | 650 | 62 | 66 | 64 | 31 | 34 | 33 | 65 | 69 | 29 | 29 | 26 | 21 | 22 | 15 | 17 |
| 9.45 | | 280 | | 64 | 69 | 66 | 31 | 34 | 33 | 66 | 71 | 29 | 32 | 29 | 21 | 26 | 26 | 24 |
| 9.5 | C | 520 | 464 | 65 | 69 | 67 | 31 | 34 | 33 | 31 | 37 | 29 | 33 | 30 | 22 | 28 | 29 | 28 |
| 10 | | 520 | 161 | 64 | 69 | 67 | 31 | 34 | 33 | 31 | 36 | 29 | 322 | 29 | 22 | 28 | 29 | 28 |
| 10.1 | | 520 | | 64 | 69 | 67 | 31 | 34 | 33 | 32 | 36 | 29 | 33 | 29 | 22 | 28 | 30 | 29 |
| 10.15 | H | 160 | 609 | 62 | 67 | 64 | 31 | 34 | 33 | 65 | 68 | 30 | 29 | 26 | 20 | 22 | 14 | 16 |
| 10.2 | | 110 | | 63 | 68 | 66 | 31 | 34 | 33 | 65 | 70 | 30 | 32 | 28 | 21 | 24 | 23 | 21 |

**Date: 11/02/2017**

| TIME | Cycle | Pressure | Flow Rate | Temperature of Hot Water (Degree C) | | TH | Temperature of cold Water (Degree C) | | TC | Temp. of Water at Entry & Exit of Bed (Degree C) | | Condenser Temp. (Degree C) | | | Evaporator Temp. (Degree C) | | | Bed |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | (heating/Cooling) | (mm of Hg) | (kg/hour) | | | | | | | | | Water | Meth_in | Meth_out | Water | Meth_in | Meth_out | Meth_in |
| | | | | Tw | T12 | | Tt | T11 | | T21 | T13 | T28 | T22 | T26 | T27 | T25 | T24 | T23 |
| 6.40 pm | H | 530 | | 47 | 49 | 48 | 29 | 29 | 29 | 28 | 31 | 26 | 34 | 27 | 29 | 28 | 27 | 27 |
| 6.50 | | 400 | | 47 | 50 | 48 | 29 | 29 | 29 | 49 | 51 | 27 | 33 | 28 | 29 | 27 | 28 | 26 |
| 7.00 | | 365 | | 50 | 53 | 51 | 29 | 31 | 30 | 51 | 54 | 28 | 32 | 29 | 29 | 28 | 29 | 26 |
| 7.15 | C | 530 | 157 | 53 | 57 | 55 | 30 | 33 | 31 | 30 | 35 | 27 | 32 | 29 | 28 | 28 | 30 | 28 |
| 7.20 | | 530 | 108 | 55 | 60 | 57 | 30 | 33 | 32 | 31 | 36 | 28 | 32 | 29 | 28 | 28 | 30 | 29 |
| 7.25 | | 530 | | 56 | 61 | 58 | 30 | 34 | 32 | 31 | 36 | 28 | 32 | 29 | 28 | 29 | 31 | 29 |
| 7.30 | H | 370 | | 55 | 60 | 58 | 31 | 35 | 33 | 56 | 57 | 28 | 29 | 26 | 28 | 23 | 18 | 20 |
| 7.35 | | 300 | | 56 | 61 | 58 | 31 | 35 | 33 | 56 | 60 | 28 | 30 | 27 | 27 | 24 | 20 | 20 |
| 7.45 | C | 510 | 113 | 58 | 63 | 61 | 31 | 35 | 33 | 30 | 38 | 28 | 32 | 29 | 27 | 28 | 29 | 28 |
| 7.55 | | 510 | 133 | 61 | 66 | 64 | 31 | 35 | 33 | 31 | 37 | 28 | 32 | 29 | 27 | 29 | 31 | 29 |
| 8.05 | | 510 | | 64 | 68 | 66 | 30 | 35 | 32 | 31 | 38 | 28 | 33 | 29 | 27 | 29 | 31 | 30 |
| 8.10 | H | 300 | 138 | 61 | 67 | 64 | 30 | 35 | 32 | 62 | 64 | 28 | 29 | 26 | 25 | 23 | 17 | 19 |
| 8.15 | | 160 | | 62 | 69 | 65 | 30 | 35 | 32 | 63 | 68 | 28 | 30 | 28 | 25 | 24 | 22 | 20 |
| 8.20 | C | 510 | 114 | 63 | 69 | 66 | 30 | 35 | 32 | 30 | 52 | 29 | 32 | 29 | 25 | 27 | 27 | 25 |
| 8.30 | | 520 | 112 | 65 | 70 | 68 | 30 | 35 | 32 | 93 | 37 | 29 | 32 | 29 | 25 | 28 | 30 | 28 |
| 8.40 | | 520 | | 65 | 70.O | 65 | 31 | 35 | 33 | 31 | 37 | 29 | 32 | 29 | 25 | 29 | 31 | 30 |
| 8.45 | H | 300 | 160 | 62 | 67 | 65 | 31 | 35 | 33 | 63 | 64 | 29 | 29 | 26 | 25 | 23 | 17 | 18 |
| 8.55 | | 100 | | 64 | 70 | 67 | 31 | 35 | 33 | 65 | 70 | 29 | 32 | 29 | 24 | 25 | 26 | 23 |
| 9.10 | C | 510 | 77 | 65 | 69 | 67 | 30 | 34 | 32 | 30 | 37 | 29 | 33 | 29 | 24 | 28 | 30 | 28 |
| 9.20 | | 520 | 110 | 65 | 69 | 67 | 30 | 34 | 32 | 31 | 36 | 29 | 33 | 29 | 24 | 28 | 30 | 29 |
| 9.30 | | 520 | | 65 | 69 | 67 | 30 | 34 | 32 | 32 | 30 | 29 | 33 | 29 | 24 | 28 | 30 | 30 |
| 9.35 | H | 170 | 650 | 62 | 66 | 64 | 31 | 34 | 33 | 65 | 69 | 29 | 29 | 26 | 21 | 22 | 15 | 17 |
| 9.45 | | 280 | | 64 | 69 | 66 | 31 | 34 | 33 | 66 | 71 | 29 | 32 | 29 | 21 | 26 | 26 | 24 |
| 9.50 | C | 520 | 464 | 65 | 69 | 67 | 31 | 34 | 33 | 31 | 37 | 29 | 33 | 30 | 22 | 28 | 29 | 28 |
| 10.00 | | 520 | 161 | 64 | 69 | 67 | 31 | 34 | 33 | 31 | 36 | 29 | 322 | 29 | 22 | 28 | 29 | 28 |
| 10.10 | | 520 | | 64 | 69 | 67 | 31 | 34 | 33 | 32 | 36 | 29 | 33 | 29 | 22 | 28 | 30 | 29 |
| 10.15 | H | 160 | 609 | 62 | 67 | 64 | 31 | 34 | 33 | 65 | 68 | 30 | 29 | 26 | 20 | 22 | 14 | 16 |
| 10.20 | | 110 | | 63 | 68 | 66 | 31 | 34 | 33 | 65 | 70 | 30 | 32 | 28 | 21 | 24 | 23 | 21 |

**Date: 18/02/2017**

| TIME | Cycle | Pressure | Flow Rate | Temperature of Hot Water (Degree C) | | TH | Temperature of cold Water (Degree C) | | TC | Temp. of Water at Entry & Exit of Bed (Degree C) | | Condenser Temp. (Degree C) | | | Evaporator Temp. (Degree C) | | | Bed |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | (heating/Cooling) | (mm of Hg) | (kg/ hour) | | | | | | | | | Water | Meth_ in | Meth_ out | Water | Meth _in | Meth_ out | Meth_ in |
| | | | | Tw | T12 | | Tt | T11 | | T21 | T13 | T28 | T22 | T26 | T27 | T25 | T24 | T23 |
| 6.20 pm | | 475 | | 53 | 52.9 | 53.0 | 32 | 30.6 | 31.3 | 27.6 | 36.5 | 25.6 | 30 | 27.4 | 29.1 | 26.8 | 29.5 | 28.1 |
| 6.3 | H | 330 | 380 | 53 | 53.6 | 53.3 | 32 | 30.9 | 31.5 | 46 | 54.8 | 26 | 28.5 | 28.1 | 29.4 | 26.7 | 30.2 | 28.2 |
| 6.4 | | 255 | | 55 | 57.1 | 56.1 | 32 | 32.5 | 32.3 | 47.8 | 58.4 | 26.3 | 28.4 | 28.8 | 29.6 | 26.6 | 30.8 | 27.6 |
| 6.45 | C | 480 | 331 | 57 | 58.8 | 57.9 | 32 | 32.9 | 32.5 | 23 | 35 | 26.1 | 28.4 | 29.1 | 29.1 | 26.7 | 31.2 | 28.1 |
| 6.55 | | 500 | 180 | 58 | 62.1 | 60.1 | 33 | 34.3 | 33.7 | 24.1 | 36.4 | 26 | 30.3 | 28.6 | 28.3 | 27.4 | 30.5 | 28.4 |
| 7.5 | | 500 | 300 | 61 | 64.8 | 62.9 | 33 | 35.2 | 34.1 | 25 | 37.1 | 26.3 | 28.7 | 29.1 | 28.4 | 27.8 | 31.7 | 30 |
| 7.1 | H | 260 | 247 | 59 | 63.4 | 61.2 | 33 | 35.5 | 34.3 | 52.4 | 63.7 | 26.3 | 28.7 | 29.1 | 28 | 27 | 31.3 | 29.3 |
| 7.2 | | 170 | | 61 | 66.5 | 63.8 | 33 | 36.1 | 34.6 | 54.7 | 66.7 | 26.5 | 28.7 | 29.1 | 27.7 | 26.4 | 30.8 | 27.6 |
| 7.25 | C | 475 | 327 | 62 | 67.7 | 64.9 | 33 | 36.3 | 34.7 | 24.8 | 37.7 | 26.4 | 28.9 | 29.4 | 27.3 | 26.7 | 31 | 28.1 |
| 7.35 | | 475 | | 62 | 70.5 | 66.3 | 33 | 36.3 | 34.7 | 25.2 | 38 | 26.2 | 28.7 | 29.3 | 26.8 | 27 | 31.6 | 29.1 |
| 7.45 | | 480 | | 65 | 70.3 | 67.7 | 33 | 36.6 | 34.8 | 26.1 | 38.6 | 26.1 | 29 | 29.4 | 26.5 | 27.3 | 31.7 | 29.8 |
| 7.5 | H | 220 | 192 | 63 | 68.4 | 65.7 | 33 | 36.4 | 34.7 | 57.6 | 67.3 | 26.5 | 29.2 | 29.9 | 26.8 | 27 | 31.5 | 29 |
| 8 | | 330 | | 65 | 70.1 | 67.6 | 33 | 36.5 | 34.8 | 40.2 | 52.4 | 26.6 | 29.4 | 30 | 26.7 | 26.9 | 31.2 | 27.7 |
| 8.05 | C | 475 | 217 | 65 | 70.1 | 67.6 | 33 | 38.8 | 35.9 | 25.9 | 38.5 | 26.4 | 29.3 | 30.1 | 26.4 | 27 | 31.4 | 28.4 |
| 8.15 | | 480 | | 65 | 70.1 | 67.6 | 32 | 36.5 | 34.3 | 26.4 | 38.3 | 26 | 29 | 29.5 | 26 | 27.2 | 31.7 | 29.1 |
| 8.25 | | 480 | 276 | 65 | 69.9 | 67.5 | 32 | 36.4 | 34.2 | 26.7 | 38.5 | 25.9 | 28.9 | 29.5 | 25.7 | 27.3 | 31.6 | 29.8 |
| 8.3 | H | 200 | 228 | 63 | 68.2 | 65.6 | 32 | 36.4 | 34.2 | 58.7 | 69.4 | 26.2 | 29.6 | 30.2 | 26 | 27 | 31.2 | 28.9 |
| 8.4 | | 100 | | 65 | 70.4 | 67.7 | 32 | 36.5 | 34.3 | 60.3 | 71.4 | 26.3 | 29.6 | 30.1 | 26.2 | 26.8 | 31 | 27.5 |
| 8.45 | C | 480 | 263 | 65 | 70.4 | 67.7 | 32 | 36.4 | 34.2 | 26.6 | 38.5 | 26.2 | 29.9 | 30.4 | 26 | 27.3 | 31.1 | 28.2 |
| 8.55 | | 480 | 298 | 65 | 70.3 | 67.7 | 32 | 36..8 | 32.0 | 26.8 | 37.9 | 25.9 | 29.4 | 30 | 25.5 | 27.5 | 31.4 | 29.1 |
| 9 | | 480 | | 65 | 70.2 | 67.6 | 32 | 36.4 | 34.2 | 27 | 38.2 | 25.9 | 29.3 | 29.9 | 25.4 | 27.7 | 31.7 | 29.6 |
| 9.05 | H | 420 | 183 | 64 | 69.9 | 67.0 | 32 | 36.8 | 34.4 | 44.8 | 44.1 | 25.6 | 29.6 | 29.8 | 25.4 | 27.8 | 31.8 | 30.1 |
| 9.15 | | 220 | | 64 | 69.7 | 66.9 | 32 | 36.5 | 34.3 | 60 | 60.4 | 26 | 29.8 | 30.1 | 25.3 | 27.5 | 31.5 | 29.4 |
| 9.2 | C | 480 | 323 | 65 | 71.2 | 68.1 | 32 | 36.4 | 34.2 | 27.5 | 39.1 | 25.9 | 30.5 | 30.5 | 25.4 | 27.3 | 31.1 | 28.9 |
| 9.3 | | 480 | 254 | 66 | 71.8 | 68.9 | 32 | 36.7 | 34.4 | 27 | 38.3 | 25.6 | 29.9 | 29.9 | 25 | 27.4 | 31 | 29 |
| 9.4 | | 480 | | 66 | 71.7 | 68.9 | 32 | 36.5 | 34.3 | 27.6 | 38.6 | 25.4 | 29.6 | 29.7 | 24.6 | 27.4 | 31.1 | 29.4 |
| 9.45 | H | 190 | 247 | 64 | 71.3 | 67.7 | 32 | 37.1 | 34.6 | 60.4 | 70.4 | 25.8 | 30.4 | 30.2 | 25.2 | 27 | 30.6 | 28.2 |
| 9.55 | | 60 | | 66 | 72.1 | 69.1 | 32 | 36.6 | 34.3 | 62.2 | 72.7 | 25.9 | 30.2 | 30 | 24.9 | 26.8 | 30.6 | 27.2 |
| 10 | C | 475 | 272 | 66 | 71.6 | 68.8 | 32 | 36.6 | 34.3 | 27.4 | 37.9 | 25.5 | 30.4 | 30.1 | 25 | 27.1 | 30.6 | 28.4 |
| 10.1 | | 480 | | 66 | 71.6 | 68.8 | 32 | 36.8 | 34.4 | 28.2 | 38 | 25.7 | 30.4 | 30 | 24.8 | 27.8 | 31.2 | 29.1 |
| 10.2 | | 480 | | 66 | 71.3 | 68.7 | 32 | 36.5 | 34.3 | 28.8 | 38.5 | 25.4 | 30.2 | 29.8 | 24.6 | 27.9 | 31.4 | 29.8 |
| 10.25 | H | 210 | 218 | 64 | 69.2 | 66.6 | 32 | 36.3 | 34.2 | 61.3 | 69 | 25.7 | 30.8 | 30.2 | 24.9 | 27.4 | 30.9 | 29 |
| 10.35 | | 80 | | 65 | 71.3 | 68.2 | 32 | 36.3 | 34.2 | 63 | 72.5 | 25.6 | 30.5 | 30.1 | 24.9 | 27.1 | 30.4 | 27.4 |
| 10.4 | C | 480 | 300 | 66 | 71.4 | 68.7 | 32 | 36.3 | 34.2 | 27.7 | 38.4 | 25.4 | 30.7 | 30.1 | 24.5 | 27.1 | 30.4 | 27.8 |
| 11 | | 480 | 268 | 65 | 69.8 | 67.4 | 32 | 34.6 | 33.3 | 29.2 | 36.5 | 25.3 | 33.3 | 28.9 | 23.8 | 28.2 | 29 | 28.5 |
| 11.05 | H | 250 | 281 | 63 | 68.1 | 65.6 | 32 | 34.5 | 33.3 | 60.9 | 68.8 | 25.5 | 31.7 | 29.1 | 23.2 | 27.6 | 29.6 | 28.3 |
| 11.15 | | 100 | | 65 | 69.3 | 67.2 | 32 | 35.3 | 33.7 | 63.2 | 70.8 | 25.9 | 31.7 | 29.5 | 24.2 | 26.8 | 29.5 | 27.1 |
| 11.2 | C | 475 | 295 | 66 | 70.4 | 68.2 | 32 | 35.5 | 33.8 | 29.2 | 37.5 | 25.8 | 31.8 | 29.9 | 24.2 | 27.2 | 30.1 | 27.7 |
| 11.3 | | 480 | | 66 | 71.1 | 68.6 | 32 | 35.8 | 33.9 | 29.5 | 37.5 | 25.6 | 31.3 | 29.8 | 24.2 | 27.6 | 30.1 | 28.8 |
| 11.4 | | 480 | | 67 | 72.5 | 69.8 | 32 | 36.2 | 34.1 | 30.2 | 38 | 25.7 | 31.4 | 29.8 | 24 | 27.9 | 30.9 | 39.5 |

**Date: 22/02/2017**

| TIME | Cycle | Pressure | Flow Rate | Temperature of Hot Water (Degree C) | | TH | Temperature of cold Water (Degree C) | | TC | Temp. of Water at Entry & Exit of Bed (Degree C) | | Condenser Temp. (Degree C) | | | Evaporator Temp. (Degree C) | | | Bed |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | (heating/Cooling) | (mm of Hg) | (kg/hour) | | | | | | | | | Water | Meth_in | Meth_out | Water | Meth_in | Meth_out | Meth_in |
| | | | | Tw | T12 | | Tt | T11 | | T21 | T13 | T28 | T22 | T26 | T27 | T25 | T24 | T23 |
| 6.30pm | H | 490 | | 49 | 50 | 49 | 30 | 29 | 30 | 28 | 33 | 27 | 33 | 27 | 28 | 27 | 28 | 28 |
| 6.40 | | 370 | 177 | 48 | 51 | 49 | 31 | 31 | 31 | 47 | 51 | 27 | 32 | 27 | 28 | 27 | 29 | 28 |
| 6.55 | C | 475 | 150 | 52 | 56 | 54 | 31 | 33 | 32 | 29 | 37 | 27 | 32 | 29 | 28 | 27 | 30 | 28 |
| 7.10 | C | 475 | | 55 | 61 | 58 | 32 | 36 | 34 | 29 | 38 | 27 | 31 | 29 | 27 | 27 | 30 | 29 |
| 7.20 | H | 300 | 144 | 55 | 61 | 58 | 32 | 36 | 34 | 53 | 60 | 27 | 32 | 29 | 27 | 27 | 29 | 28 |
| 7.35 | C | 475 | 142 | 59 | 65 | 62 | 32 | 37 | 34 | 30 | 39 | 27 | 31 | 28 | 27 | 27 | 30 | 29 |
| 7.50 | C | 475 | | 61 | 68 | 64 | 32 | 37 | 34 | 30 | 39 | 26 | 31 | 28 | 26 | 27 | 30 | 29 |
| 8.00 | H | 210 | 206 | 60 | 66 | 63 | 32 | 37 | 35 | 59 | 68 | 26 | 31 | 28 | 26 | 26 | 29 | 27 |
| 8.15 | C | 475 | 220 | 61 | 68 | 64 | 32 | 37 | 35 | 30 | 39 | 26 | 31 | 28 | 25 | 27 | 29 | 28 |
| 8.30 | C | 475 | | 61 | 68 | 64 | 32 | 36 | 34 | 30 | 39 | 26 | 31 | 28 | 25 | 27 | 29 | 28 |
| 8.40 | H | 225 | 202 | 58 | 65 | 61 | 32 | 37 | 34 | 57 | 66 | 26 | 31 | 28 | 25 | 26 | 28 | 27 |
| 8.55 | C | 475 | 170 | 58 | 65 | 61 | 32 | 37 | 34 | 30 | 38 | 25 | 31 | 28 | 24 | 26 | 29 | 27 |
| 9.10 | C | 475 | | 58 | 64 | 61 | 32 | 37 | 34 | 31 | 39 | 25 | 31 | 28 | 24 | 26 | 29 | 28 |
| 9.20 | H | 280 | 150 | 56 | 62 | 59 | 32 | 37 | 34 | 55 | 64 | 25 | 31 | 28 | 24 | 26 | 28 | 27 |
| 9.35 | C | 475 | 170 | 57 | 63 | 60 | 32 | 37 | 34 | 30 | 39 | 25 | 31 | 28 | 24 | 26 | 28 | 27 |
| 9.50 | C | 475 | | 57 | 63 | 60 | 32 | 37 | 34 | 31 | 39 | 24 | 31 | 28 | 23 | 26 | 28 | 27 |
| 10.00 | H | 265 | 165 | 56 | 63 | 60 | 32 | 37 | 35 | 55 | 64 | 24 | 31 | 27 | 23 | 26 | 27 | 26 |
| 10.15 | C | 475 | 215 | 57 | 63 | 60 | 32 | 37 | 34 | 30 | 39 | 24 | 31 | 27 | 22 | 25 | 27 | 26 |
| 10.30 | C | 475 | | 57 | 63 | 60 | 32 | 37 | 35 | 30 | 39 | 24 | 31 | 27 | 22 | 25 | 27 | 26 |
| 10.40 | H | 300 | 205 | 56 | 62 | 59 | 32 | 37 | 35 | 55 | 64 | 24 | 30 | 27 | 22 | 25 | 27 | 27 |
| 10.55 | C | 475 | 222 | 57 | 64 | 60 | 32 | 37 | 35 | 30 | 39 | 23 | 31 | 27 | 21 | 25 | 27 | 26 |
| 11.10 | C | 475 | | 57 | 64 | 60 | 32 | 37 | 35 | 30 | 39 | 23 | 30 | 26 | 21 | 25 | 26 | 26 |
| 11.20 | H | 275 | 160 | 57 | 63 | 60 | 32 | 37 | 35 | 56 | 64 | 23 | 30 | 26 | 21 | 24 | 26 | 25 |
| 11.35 | C | 475 | 221 | 57 | 64 | 60 | 32 | 37 | 35 | 30 | 39 | 23 | 30 | 26 | 20 | 24 | 26 | 25 |
| 11.50 | C | 475 | | 57 | 64 | 60 | 32 | 37 | 35 | 30 | 39 | 23 | 30 | 26 | 20 | 25 | 26 | 25 |
| 12.00 | H | 290 | 171 | 56 | 63 | 60 | 32 | 37 | 35 | 56 | 65 | 23 | 30 | 26 | 20 | 24 | 25 | 25 |
| 12.15 | C | 475 | 221 | 57 | 64 | 61 | 32 | 37 | 35 | 30 | 39 | 22 | 30 | 26 | 20 | 24 | 25 | 25 |
| 12.30 | C | 475 | | 57 | 64 | 61 | 31 | 37 | 34 | 30 | 39 | 22 | 30 | 25 | 19 | 24 | 25 | 26 |

**Date: 14/03/2017**

| TIME | Cycle | Pressure | Flow Rate | Temperature of Hot Water (Degree C) | | TH | Temperature of cold Water (Degree C) | | TC | Temp. of Water at Entry & Exit of Bed (Degree C) | | Condenser Temp. (Degree C) | | | Evaporator Temp. (Degree C) | | | Bed |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | (heating/Cooling) | (mm of Hg) | (kg/ hour) | | | | | | | | | Water | Meth_ in | Meth_ out | Water | Meth _in | Meth_ out | Meth_ in |
| | | | | Tw | T12 | | Tt | T11 | | T21 | T13 | T28 | T22 | T26 | T27 | T25 | T24 | T23 |
| 6.45 pm | H | 480 | | 51 | 49 | 50 | 31 | 29 | 30 | 28 | 33 | 27.1 | 33 | 27 | 29.5 | 27.3 | 28.1 | 27.8 |
| 6.55 | H | 375 | 165 | 50 | 50 | 50 | 32 | 31 | 31 | 47 | 51 | 27.6 | 32 | 27 | 29.8 | 26.9 | 28.9 | 28.2 |
| 7.10 | C | 470 | 150 | 54 | 55 | 54 | 32 | 33 | 32 | 29 | 37 | 27.7 | 32 | 29 | 28.6 | 27.2 | 29.8 | 28.1 |
| 7.25 | C | 470 | | 57 | 60 | 58 | 33 | 36 | 34 | 29 | 38 | 27.6 | 31 | 29 | 27.9 | 27.4 | 30.2 | 29.2 |
| 7.35 | H | 290 | 145 | 57 | 60 | 58 | 33 | 36 | 34 | 53 | 60 | 27.3 | 32 | 29 | 26.9 | 27 | 29.4 | 28.1 |
| 7.50 | C | 480 | 142 | 61 | 64 | 62 | 33 | 37 | 35 | 30 | 39 | 27.3 | 31 | 28 | 26.5 | 27 | 29.6 | 28.7 |
| 8.05 | C | 480 | | 63 | 67 | 65 | 33 | 37 | 35 | 30 | 39 | 26.9 | 31 | 28 | 25.7 | 26.9 | 29.5 | 28.7 |
| 8.15 | H | 200 | 190 | 62 | 66 | 64 | 33 | 37 | 35 | 59 | 68 | 26.8 | 31 | 28 | 25.6 | 26.3 | 28.8 | 27.3 |
| 8.30 | C | 480 | 210 | 63 | 67 | 65 | 33 | 37 | 35 | 30 | 39 | 26.6 | 31 | 28 | 24.8 | 26.5 | 28.9 | 27.8 |
| 8.45 | C | 480 | | 63 | 67 | 65 | 33 | 36 | 34 | 30 | 39 | 26.3 | 31 | 28 | 24.6 | 26.6 | 29 | 28.3 |
| 8.55 | H | 220 | 200 | 60 | 64 | 62 | 33 | 37 | 35 | 57 | 66 | 26.2 | 31 | 28 | 24.2 | 26 | 28.2 | 26.8 |
| 9.10 | C | 475 | 180 | 60 | 64 | 62 | 33 | 37 | 35 | 30 | 38 | 25.7 | 31 | 28 | 23.9 | 26 | 28.5 | 27.2 |
| 9.25 | C | 480 | | 60 | 64 | 62 | 33 | 37 | 35 | 31 | 39 | 25.6 | 31 | 28 | 23.7 | 26.1 | 28.6 | 27.7 |
| 9.35 | H | 270 | 140 | 58 | 62 | 60 | 33 | 37 | 35 | 55 | 64 | 25.3 | 31 | 28 | 23.5 | 25.7 | 27.9 | 26.7 |
| 9.50 | C | 480 | 160 | 59 | 63 | 61 | 33 | 37 | 35 | 30 | 39 | 25.1 | 31 | 28 | 23.2 | 25.9 | 27.8 | 26.9 |
| 10.05 | C | 475 | | 59 | 63 | 61 | 33 | 37 | 35 | 31 | 39 | 24.9 | 31 | 28 | 22.8 | 25.8 | 28 | 27.2 |
| 10.15 | H | 280 | 160 | 58 | 63 | 60 | 33 | 37 | 35 | 55 | 64 | 24.6 | 31 | 27 | 22.4 | 25.5 | 27.2 | 26.1 |
| 10.30 | C | 480 | 200 | 59 | 63 | 61 | 33 | 37 | 35 | 30 | 39 | 24.4 | 31 | 27 | 21.7 | 25.3 | 27.2 | 26.2 |
| 10.45 | C | 475 | | 59 | 63 | 61 | 33 | 37 | 35 | 30 | 39 | 24.1 | 31 | 27 | 21.5 | 25.4 | 27 | 26.4 |
| 10.55 | H | 290 | 190 | 58 | 62 | 60 | 33 | 37 | 35 | 55 | 64 | 24 | 30 | 27 | 21.1 | 25 | 26.5 | 26.9 |
| 11.10 | C | 480 | 180 | 59 | 63 | 61 | 33 | 37 | 35 | 30 | 39 | 23.7 | 31 | 27 | 20.6 | 24.8 | 26.5 | 25.7 |
| 11.25 | C | 480 | | 59 | 63 | 61 | 33 | 37 | 35 | 30 | 39 | 23.4 | 30 | 26 | 20.4 | 24.9 | 26.2 | 25.8 |
| 11.35 | H | 475 | 160 | 59 | 63 | 61 | 33 | 37 | 35 | 56 | 64 | 23.5 | 30 | 26 | 19.9 | 24.2 | 25.8 | 24.9 |
| 11.50 | C | 475 | 190 | 59 | 63 | 61 | 33 | 37 | 35 | 30 | 39 | 23.2 | 30 | 26 | 19.6 | 24.3 | 25.5 | 25.1 |
| 12.05 | C | 480 | | 59 | 63 | 61 | 33 | 37 | 35 | 30 | 39 | 23 | 30 | 26 | 19.5 | 24.5 | 25.9 | 25.4 |
| 12.15 | H | 270 | 180 | 58 | 63 | 60 | 33 | 37 | 35 | 56 | 65 | 23.1 | 30 | 26 | 19.1 | 24.1 | 25.4 | 24.7 |
| 12.30 | C | 480 | 210 | 59 | 64 | 61 | 33 | 37 | 35 | 30 | 39 | 22.8 | 30 | 26 | 18.4 | 24.3 | 25.3 | 24.7 |
| 12.45 | C | 475 | | 59 | 64 | 61 | 32 | 37 | 34 | 30 | 39 | 22.7 | 30 | 25 | 18.1 | 24.2 | 25.1 | 25.6 |

**Date: 15/03/2017**

| TIME | Cycle | Pressure | Flow Rate | Temperature of Hot Water (Degree C) | | TH | Temperature of cold Water (Degree C) | | TC | Temp. of Water at Entry & Exit of Bed (Degree C) | | Condenser Temp. (Degree C) | | | Evaporator Temp. (Degree C) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | (heating/ Cooling) | (mm of Hg) | (kg/ hour) | | | | | | | | | Water | Meth_ in | Meth_ out | Water | Meth _in | Meth_ out |
| | | | | Tw | T12 | | Tt | T11 | | T21 | T13 | T28 | T22 | T26 | T27 | T25 | T24 |
| 6.40 pm | H | 535 | | 48 | 48 | 48 | 28 | 30.6 | 29.3 | 28.4 | 31 | 25.2 | 33.6 | 27 | 29.7 | 27.7 | 27.2 |
| 6.50 | | 390 | | 48 | 49 | 48.5 | 28 | 31.2 | 29.6 | 48.8 | 50.9 | 26 | 32.9 | 28.2 | 30.1 | 26.9 | 28 |
| 7.05 | | 370 | | 51 | 52 | 51.55 | 28 | 32.7 | 30.35 | 50.5 | 53.7 | 26.8 | 32.1 | 29.3 | 30.3 | 27.6 | 28.7 |
| 7.20 | C | 532 | 450 | 54 | 57 | 55.35 | 29 | 34.5 | 31.75 | 29.7 | 34.7 | 26.4 | 32.2 | 28.5 | 29 | 28 | 29.7 |
| 7.25 | | 532 | 370 | 56 | 59 | 57.5 | 29 | 35.3 | 32.15 | 30.6 | 35.8 | 26.7 | 32.3 | 29.1 | 29.2 | 28.4 | 30.3 |
| 7.30 | | 535 | | 57 | 60 | 58.7 | 29 | 35.8 | 32.4 | 31 | 36.4 | 26.6 | 32.3 | 29.3 | 29 | 28.5 | 30.7 |
| 7.35 | H | 375 | | 56 | 60 | 57.85 | 30 | 36.6 | 33.3 | 55.6 | 57.1 | 26.8 | 29.2 | 26.3 | 28.5 | 23.4 | 18.4 |
| 7.40 | | 310 | | 57 | 60 | 58.7 | 30 | 36.7 | 33.35 | 56.1 | 60.4 | 26.8 | 29.7 | 26.9 | 28.3 | 23.7 | 20.1 |
| 7.50 | C | 515 | 400 | 59 | 63 | 60.85 | 30 | 36.9 | 33.45 | 30 | 37.5 | 27.1 | 32.3 | 29.2 | 28 | 27.5 | 29.3 |
| 8.00 | | 515 | 470 | 62 | 66 | 63.85 | 30 | 37.1 | 33.55 | 31 | 37.4 | 27.2 | 32 | 29.2 | 25.9 | 28.6 | 30.5 |
| 8.10 | | 515 | | 65 | 68 | 66.3 | 29 | 36.7 | 32.85 | 31.4 | 37.9 | 27.2 | 32.5 | 29.4 | 25.8 | 28.6 | 30.8 |
| 8.15 | H | 295 | 140 | 62 | 67 | 64.4 | 29 | 36.9 | 32.95 | 62.4 | 64.3 | 27.3 | 28.7 | 26.1 | 24.2 | 23.4 | 17.1 |
| 8.20 | | 170 | | 63 | 68 | 65.5 | 29 | 36.9 | 32.95 | 62.9 | 68.3 | 27.3 | 30.2 | 27.6 | 24.1 | 24 | 21.7 |
| 8.25 | C | 510 | 410 | 64 | 68 | 66 | 29 | 36.9 | 32.95 | 30 | 52.3 | 27.5 | 32.3 | 29.4 | 23.9 | 26.7 | 27.3 |
| 8.35 | | 515 | 400 | 66 | 70 | 67.8 | 29 | 36.5 | 32.75 | 92.7 | 36.8 | 27.5 | 32.4 | 29.4 | 23.9 | 27.9 | 29.5 |
| 8.45 | | 515 | | 66 | 70 | 67.75 | 30 | 36.8 | 33.4 | 31.1 | 37.2 | 27.6 | 32.4 | 29.4 | 24 | 28.5 | 30.6 |
| 8.50 | H | 310 | 170 | 63 | 67 | 64.85 | 30 | 36.8 | 33.4 | 63.1 | 64.2 | 27.6 | 29 | 26.2 | 23.6 | 23.1 | 16.7 |
| 9.00 | | 90 | | 65 | 69 | 67.05 | 30 | 36.7 | 33.35 | 64.9 | 69.9 | 27.9 | 31.9 | 29 | 22.9 | 25.4 | 26.3 |
| 9.15 | C | 500 | 220 | 66 | 69 | 67.3 | 29 | 36 | 32.5 | 30.1 | 36.6 | 27.8 | 32.5 | 29.3 | 22.7 | 27.9 | 29.7 |
| 9.25 | | 515 | 390 | 66 | 69 | 67.45 | 29 | 35.6 | 32.3 | 30.8 | 35.8 | 28 | 32.5 | 29.3 | 22.6 | 28.3 | 30.2 |
| 9.35 | | 515 | | 66 | 68 | 67.15 | 29 | 35.9 | 32.45 | 31.7 | 30.4 | 27.9 | 32.5 | 29.1 | 22.7 | 28.4 | 30.3 |
| 9.40 | H | 175 | 430 | 63 | 66 | 64.45 | 30 | 36.2 | 33.1 | 64.5 | 68.6 | 28.3 | 29 | 25.8 | 19.7 | 22.4 | 14.7 |
| 9.50 | | 290 | | 65 | 68 | 66.6 | 30 | 36.2 | 33.1 | 65.9 | 70.6 | 28.4 | 32.1 | 29 | 20.2 | 25.9 | 26.1 |
| 9.55 | C | 510 | 400 | 66 | 68 | 67.1 | 30 | 36.2 | 33.1 | 30.7 | 36.5 | 28.4 | 32.9 | 29.6 | 20.6 | 27.7 | 28.9 |
| 10.05 | | 510 | 380 | 65 | 69 | 66.9 | 30 | 36.3 | 33.15 | 31 | 35.8 | 28.2 | 321.6 | 29.1 | 20.7 | 27.9 | 29.3 |
| 10.15 | | 510 | | 65 | 69 | 66.85 | 30 | 36.2 | 33.1 | 31.7 | 36.2 | 28.3 | 32.5 | 28.8 | 20.7 | 28.1 | 29.6 |
| 10.2 | H | 170 | 390 | 63 | 66 | 64.55 | 30 | 36.4 | 33.2 | 64.5 | 68.4 | 28.6 | 29.1 | 25.5 | 19.4 | 21.7 | 14.1 |
| 10.25 | | 100 | | 64 | 68 | 65.75 | 31 | 36.4 | 33.7 | 65.2 | 69.7 | 28.6 | 31.8 | 28.2 | 19.5 | 24.3 | 23 |

**Date: 20/03/2017**

| TIME | Cycle (heating/Cooling) | Pressure (mm of Hg) | Flow Rate (kg/hour) | Temperature of Hot Water (Degree C) | | TH | Temperature of cold Water (Degree C) | | TC | Temp. of Water at Entry & Exit of Bed (Degree C) | | Condenser Temp. (Degree C) | | | Evaporator Temp. (Degree C) | | | Bed |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | Water | Meth_in | Meth_out | Water | Meth_in | Meth_out | Meth_in |
| | | | | Tw | T12 | | Tt | T11 | | T21 | T13 | T28 | T22 | T26 | T27 | T25 | T24 | T23 |
| 7.05 pm | H | 490 | | 50 | 49 | 50 | 30 | 31 | 31 | 28 | 33 | 26.5 | 33 | 27 | 30.3 | 27.3 | 28.1 | 27.8 |
| 7.15 | H | 380 | 160 | 50 | 50 | 50 | 31 | 31 | 31 | 47 | 51 | 27.6 | 32 | 27 | 30.6 | 26.9 | 28.9 | 28.2 |
| 7.30 | C | 475 | 155 | 55 | 55 | 55 | 32 | 34 | 33 | 29 | 37 | 27.5 | 32 | 29 | 29.4 | 27.2 | 29.8 | 28.1 |
| 7.45 | C | 475 | | 56 | 60 | 58 | 32 | 35 | 34 | 29 | 38 | 27.6 | 31 | 29 | 28.7 | 27.4 | 30.2 | 29.2 |
| 7.55 | H | 295 | 150 | 57 | 60 | 58 | 33 | 36 | 34 | 53 | 60 | 27.3 | 32 | 29 | 27.7 | 27 | 29.4 | 28.1 |
| 8.10 | C | 485 | 145 | 60 | 64 | 62 | 33 | 37 | 35 | 30 | 39 | 26.5 | 31 | 28 | 26.9 | 27 | 29.6 | 28.7 |
| 8.25 | C | 490 | | 62 | 67 | 65 | 32 | 36 | 34 | 30 | 39 | 26.9 | 31 | 28 | 26.5 | 26.9 | 29.5 | 28.7 |
| 8.35 | H | 205 | 170 | 62 | 66 | 64 | 33 | 37 | 35 | 59 | 68 | 26.8 | 31 | 28 | 26.4 | 26.3 | 28.8 | 27.3 |
| 8.50 | C | 485 | 200 | 62 | 67 | 65 | 33 | 37 | 35 | 30 | 39 | 26.6 | 31 | 28 | 25.3 | 26.5 | 28.9 | 27.8 |
| 9.05 | C | 490 | | 63 | 67 | 65 | 33 | 36 | 34 | 30 | 39 | 26.3 | 31 | 28 | 25.4 | 26.6 | 29 | 28.3 |
| 9.15 | H | 220 | 190 | 60 | 64 | 62 | 32 | 37 | 34 | 57 | 66 | 26.2 | 31 | 28 | 25 | 26 | 28.2 | 26.8 |
| 9.30 | C | 480 | 175 | 60 | 63 | 61 | 33 | 37 | 35 | 30 | 38 | 25.7 | 31 | 28 | 24.7 | 26 | 28.5 | 27.2 |
| 9.45 | C | 485 | | 60 | 64 | 62 | 33 | 36 | 34 | 31 | 39 | 25.6 | 31 | 28 | 24.6 | 26.1 | 28.6 | 27.7 |
| 9.55 | H | 270 | 155 | 57 | 62 | 59 | 33 | 37 | 35 | 55 | 64 | 25.3 | 31 | 28 | 24.3 | 25.7 | 27.9 | 26.7 |
| 10.10 | C | 485 | 160 | 60 | 63 | 61 | 32 | 37 | 34 | 30 | 39 | 26.0 | 31 | 28 | 24 | 25.9 | 27.8 | 26.9 |
| 10.25 | C | 480 | | 59 | 63 | 61 | 33 | 37 | 35 | 31 | 39 | 24.9 | 31 | 28 | 23.6 | 25.8 | 28 | 27.2 |
| 10.35 | H | 285 | 165 | 57 | 62 | 60 | 33 | 35 | 34 | 55 | 64 | 24.6 | 31 | 27 | 23.2 | 25.5 | 27.2 | 26.1 |
| 10.50 | C | 485 | 180 | 59 | 63 | 61 | 33 | 36 | 34 | 30 | 39 | 24.4 | 31 | 27 | 22.4 | 25.3 | 27.2 | 26.2 |
| 11.05 | C | 485 | | 60 | 63 | 61 | 33 | 37 | 35 | 30 | 39 | 24.1 | 31 | 27 | 22.3 | 25.4 | 27 | 26.4 |
| 11.15 | H | 290 | 190 | 58 | 62 | 60 | 33 | 37 | 35 | 55 | 64 | 24.0 | 30 | 27 | 21.9 | 25 | 26.5 | 26.9 |
| 11.30 | C | 485 | 185 | 59 | 63 | 61 | 32 | 36 | 34 | 30 | 39 | 25.0 | 31 | 27 | 21.3 | 24.8 | 26.5 | 25.7 |
| 11.45 | C | 485 | | 60 | 63 | 62 | 33 | 37 | 35 | 30 | 39 | 23.4 | 30 | 26 | 21.2 | 24.9 | 26.2 | 25.8 |
| 11.55 | H | 280 | 165 | 59 | 63 | 61 | 33 | 36 | 34 | 56 | 64 | 23.5 | 30 | 26 | 20.7 | 24.2 | 25.8 | 24.9 |
| 12.10 | C | 490 | 185 | 60 | 62 | 61 | 33 | 37 | 35 | 30 | 39 | 23.2 | 30 | 26 | 20.4 | 24.3 | 25.5 | 25.1 |
| 12.25 | C | 485 | | 59 | 63 | 61 | 31 | 36 | 34 | 30 | 39 | 24.0 | 30 | 26 | 20.3 | 24.5 | 25.9 | 25.4 |
| 12.35 | H | 280 | 190 | 58 | 63 | 60 | 33 | 37 | 35 | 56 | 65 | 23.1 | 30 | 26 | 19.9 | 24.1 | 25.4 | 24.7 |
| 12.45 | C | 485 | 185 | 60 | 64 | 62 | 31 | 37 | 34 | 30 | 39 | 24.0 | 30 | 26 | 18.9 | 24.3 | 25.3 | 24.7 |
| 12.55 | C | 490 | | 59 | 63 | 61 | 32 | 36 | 34 | 30 | 39 | 22.7 | 30 | 25 | 18.5 | 24.2 | 25.1 | 25.6 |

**Date: 22/03/2017**

| TIME | Cycle (heating/Cooling) | Pressure (mm of Hg) | Flow Rate (kg/hour) | Temperature of Hot Water (Degree C) | | TH | Temperature of cold Water (Degree C) | | TC | Temp. of Water at Entry & Exit of Bed (Degree C) | | Condenser Temp. (Degree C) | | | Evaporator Temp. (Degree C) | | | Bed |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | Water | Meth_in | Meth_out | Water | Meth_in | Meth_out | Meth_in |
| | | | | Tw | T12 | | Tt | T11 | | T21 | T13 | T28 | T22 | T26 | T27 | T25 | T24 | T23 |
| 6.05 pm | H | 480 | | 52 | 48 | 50 | 29 | 30 | 30 | 29 | 32 | 26.0 | 33 | 27 | 30.7 | 27.5 | 28 | 27.5 |
| 6.15 | H | 390 | 165 | 51 | 49 | 50 | 30 | 30 | 30 | 48 | 52 | 27.5 | 32 | 27 | 31.4 | 27.1 | 29 | 28.5 |
| 6.30 | C | 480 | 160 | 49 | 53 | 51 | 31 | 33 | 32 | 30 | 37 | 27.4 | 32 | 29 | 30.1 | 27.4 | 30 | 28.4 |
| 6.45 | C | 480 | | 55 | 58 | 57 | 31 | 34 | 33 | 30 | 38 | 27.4 | 31 | 29 | 29.2 | 27.6 | 30.3 | 29.5 |
| 6.55 | H | 290 | 155 | 56 | 58 | 57 | 32 | 34 | 33 | 52 | 60 | 27.4 | 32 | 29 | 28.1 | 27.2 | 29.5 | 28.4 |
| 7.10 | C | 490 | 150 | 58 | 63 | 61 | 33 | 35 | 34 | 29 | 39 | 26.6 | 31 | 28 | 27.2 | 27.2 | 29.7 | 29 |
| 7.25 | C | 485 | | 60 | 65 | 63 | 32 | 36 | 34 | 30 | 40 | 27.0 | 31 | 28 | 26.9 | 27 | 29.6 | 29 |
| 7.35 | H | 200 | 165 | 61 | 64 | 63 | 32 | 37 | 35 | 58 | 67 | 26.7 | 31 | 28 | 26.4 | 26.5 | 29 | 27.6 |
| 7.50 | C | 480 | 180 | 61 | 65 | 63 | 33 | 35 | 34 | 30 | 39 | 26.5 | 31 | 28 | 25.3 | 26.7 | 29 | 28.1 |
| 8.05 | C | 485 | | 64 | 65 | 65 | 32 | 36 | 34 | 29 | 40 | 26.2 | 31 | 28 | 25.4 | 26.8 | 29.1 | 28.6 |
| 8.15 | H | 210 | 185 | 62 | 62 | 62 | 32 | 37 | 34 | 58 | 66 | 26.2 | 31 | 28 | 24.9 | 26.2 | 28.3 | 27 |
| 8.30 | C | 485 | 180 | 62 | 61 | 62 | 33 | 35 | 34 | 30 | 38 | 25.7 | 31 | 28 | 24.7 | 26.2 | 28.6 | 27.4 |
| 8.45 | C | 490 | | 62 | 62 | 62 | 32 | 36 | 34 | 30 | 40 | 25.6 | 31 | 28 | 24.6 | 26.3 | 28.6 | 27.9 |
| 8.55 | H | 280 | 165 | 58 | 61 | 60 | 33 | 37 | 35 | 55 | 63 | 25.2 | 31 | 28 | 24.3 | 26 | 28 | 26.9 |
| 9.10 | C | 480 | 170 | 62 | 62 | 62 | 32 | 35 | 34 | 30 | 39 | 26.0 | 31 | 28 | 24.1 | 26.1 | 27.9 | 27.1 |
| 9.25 | C | 485 | | 60 | 62 | 61 | 33 | 37 | 35 | 30 | 40 | 24.9 | 31 | 28 | 23.4 | 26 | 28.1 | 27.4 |
| 9.35 | H | 280 | 165 | 58 | 61 | 60 | 32 | 35 | 34 | 57 | 64 | 24.6 | 31 | 27 | 23 | 25.7 | 27.3 | 26.3 |
| 9.50 | C | 480 | 170 | 58 | 62 | 60 | 33 | 36 | 34 | 30 | 39 | 24.4 | 31 | 27 | 22.7 | 25.5 | 27.2 | 26.4 |
| 10.05 | C | 485 | | 61 | 62 | 62 | 32 | 37 | 35 | 31 | 40 | 24.2 | 31 | 27 | 22.3 | 25.6 | 27.1 | 26.6 |
| 10.15 | H | 295 | 185 | 59 | 61 | 60 | 33 | 35 | 34 | 55 | 64 | 24.0 | 30 | 27 | 21.8 | 25.2 | 26.6 | 27.1 |
| 10.30 | C | 480 | 180 | 60 | 62 | 61 | 32 | 36 | 34 | 30 | 39 | 25.0 | 31 | 27 | 21.3 | 25 | 26.7 | 25.8 |
| 10.45 | C | 485 | | 59 | 62 | 61 | 33 | 37 | 35 | 31 | 40 | 23.0 | 30 | 26 | 21.1 | 25.1 | 26.3 | 25.9 |
| 10.55 | H | 485 | 170 | 62 | 62 | 62 | 32 | 36 | 34 | 56 | 63 | 23.5 | 30 | 26 | 20.6 | 24.4 | 26 | 25 |
| 11.10 | C | 480 | 185 | 61 | 61 | 61 | 33 | 35 | 34 | 30 | 39 | 23.2 | 30 | 26 | 20.2 | 24.5 | 25.6 | 25.2 |
| 11.25 | C | 485 | | 60 | 61 | 61 | 31 | 36 | 34 | 31 | 39 | 24.1 | 30 | 26 | 20.1 | 24.8 | 26 | 25.5 |
| 11.35 | H | 290 | 185 | 59 | 63 | 61 | 32 | 37 | 35 | 56 | 65 | 23.5 | 30 | 26 | 19.5 | 24.3 | 25.5 | 24.8 |
| 11.45 | C | 485 | 175 | 61 | 65 | 63 | 31 | 35 | 33 | 30 | 40 | 23.8 | 30 | 26 | 18.9 | 24.5 | 25.4 | 24.8 |
| 11.55 | C | 480 | | 60 | 62 | 61 | 32 | 36 | 34 | 31 | 39 | 22.9 | 30 | 25 | 18.2 | 24.5 | 25.3 | 25.7 |

## Appendix C

## UNCERTAINTY ANALYSIS

The total uncertainty [57] ascending due to independent variable can be expressed as under

$$\omega_R = \left[\left(\frac{\partial R}{\partial x_1} \cdot \omega_1\right)^2 + \left(\frac{\partial R}{\partial x_2} \cdot \omega_2\right)^2 + \ldots\ldots\ldots\ldots\ldots\ldots.\right]^{\frac{1}{2}}$$

Where $\omega_R$ is uncertainty in result and $\omega_1$ , $\omega_1$ …. are the uncertainty in independent variables.

Table C1, shows the list of Instruments with accuracy, range and percentage of errors.

**Table C1:** List of Instruments with accuracy, range and percentage of errors

| Instrument | Accuracy | Range | % Error |
|---|---|---|---|
| K type Thermocouple | ± 0.1 $^{O}$ C | 0-400 $^{O}$ C | 0.5 |
| Dial Pressure Gauge | ± 2 cm of hg | 0-76 cm | 1 |
| Level Indicator | ±0.5 mL | 0-50 ml | 0.5 |
| Weighing Balance | ±0.01 gm | 0-500 gm | 0.01 |
| Hour Meter | ±0.01 hour ( 6 W) | 0-9999.99 hour | 0.01 |
| Measuring Beaker | ±0.5 mL | 0-1000 ml | 0.5 |

### 1. Uncertainty in Adsorption Capacity

The Adsorption capacity (X) for ACF-Methanol in adsorption water chiller is calculated by amount of methanol adsorbed in ACF during isobaric adsorption process. It is ration of mass of methanol per unit mass of ACF.

$$X = \left(\frac{M_{meth}}{M_{ACF}}\right)$$

$$\frac{\partial X}{\partial M_{meth}} = \frac{1}{M_{ACF}}$$

$$\frac{\partial X}{\partial M_{ACF}} = -\frac{M_{meth}}{M_{ACF}^2}$$

$$\omega_X = \left[\left(\frac{(1)}{(35)} \cdot (0.38)\right)^2 + \left((0.0031) \cdot (0.01)\right)^2\right]^{\frac{1}{2}}$$

$= \; 0.01083$ or 2.5 %

## 2. Uncertainty in Cooling Effect

The cooling effect produce in adsorption water chiller is calculated by drop in temperature of fixed mass of water filled in evaporator vessel in employ time.

$$Qevp = m^{\cdot} . C_p . \Delta T$$

$$Qevp = \left(\frac{10}{13500}\right). (4.2). (10.9)$$

$$Qevp = 33.91\ Watt$$

$$\omega_{Qevp} = \left[\left(\frac{(4.2).(10)}{(13500)} . (1.09)\right)^2\right]^{\frac{1}{2}}$$

$$\omega_{Qevp} = 0.0034$$

$$\%\ \omega_{Qevp} = \frac{0.0034}{33.91} . 100$$

$$\%\ \omega_{Qevp} = 0.01\ \%$$

## 3. Uncertainty in COP

The adsorption chiller COP is calculated by cooling effect ($Q_{evp}$) produce from total energy ($Q_g$) input to the system. Here total energy input are measured by calibrated hour meter and which shows the least count of 6 Watt.

$$COP = \left(\frac{Q_{evp}}{Q_g}\right)$$

$$\frac{\partial COP}{\partial Q_{evp}} = \frac{1}{Q_g}$$

$$\frac{\partial COP}{\partial Q_g} = -\frac{Q_{evp}}{Q_g^2}$$

$$\omega_{COP} = \left[\left(\frac{(1)}{(75)} . (0.0034)\right)^2 + \left((6.028^{-3}) . (6)\right)^2\right]^{\frac{1}{2}}$$

$$= 0.036 \text{ or } 8\ \%$$

## 4. Uncertainty in SCP

The specific cooling power of proposed system is determined by produced cooling effect per unit mass of ACF ($M_{acf}$). In this system, total mass of ACF is 450 grams.

$$SCP = \left(\frac{Q_{evp}}{M_{ACF}}\right)$$

$$\frac{\partial SCP}{\partial Q_{evp}} = \frac{1}{M_{ACF}}$$

$$\frac{\partial SCP}{\partial M_{ACF}} = -\ \frac{Q_{evp}}{M_{ACF}^2}$$

$$\omega_{SCP} = \left[\left(\frac{(1)}{(0.45)} \,.\, (0.0034)\right)^2 + \left((167.45)\,.\,(0.00001)\right)^2\ \right]^{\frac{1}{2}}$$

= 0.0077 or 1.71 %

The total uncertainty of various parameters are shown in below table C2.

**Table C2:** List of parameter with Total uncertainty

| **Parameters** | **Total uncertainty (%)** |
|---|---|
| adsorption capacity | 2.5 |
| Cooling Effect | 0.01 |
| COP | 8 |
| SCP | 1.71 |

# Appendix D

## List of Publications

| Sr. No | Title of the Paper | Name of the Authors | Name of Journal | ISSN Number | Month & Year of Publication |
|---|---|---|---|---|---|
| 1 | Hybrid solar water heating and adsorption refrigeration technologies - a review | Bhargav HA, Ramani BM | SESI Journal, Solar Energy Society of India | 0970-2466 | June-2016, Vol-2 |
| 2 | Experimental investigation on adsorption capacity of acf-methanol pairs for cooling application | Bhargav HA, Ramani BM, Reddy VS. | Ambient Energy, Taylor Francis Journal | 2162-8246 | May-2017 |
| 3 | Development of semi-continuous solar powered adsorption water chiller for food preservation | Bhargav HA, Ramani BM, Reddy VS., Lai FC | Journal of Thermal Engineering, Turkey SCOPUS & ESCI index | 2148-7847 | Accepted Dec-2017 |
| 4 | Experimental study on Adsorption Capacity of activated carbon based Adsorption water chiller | Bhargav HA, Ramani BM, Reddy VS. | Ambient Energy, Taylor Francis Journal | 2162-8246 | Jan-2018 |
| 5 | Solar Powered Adsorption Chiller for Cooling and Heating Application: A Review | Bhargav HA, Ramani BM, Reddy VS. | Renewable & Sustainable Energy Reviews | 1364-0321 | Revision Submitted March-18 |