Solar Adsorption Chiller for Public Health Centres

By

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09MMET16

DEPARTMENT OF MECHANICAL ENGINEERING
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NIRMA UNIVERSITY
AHMEDABAD-382481
MAY 2011

Solar Adsorption Chiller for Public Health Centres

Major Project

Submitted in partial fulfillment of the requirements

For the degree of

Master of Technology in Mechanical Engineering (Thermal Engineering)

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Declaration

This is to certify that

1. The thesis comprises my original work towards the degree of Master of Technology in Thermal Engineering at Nirma University and has not been submitted elsewhere for a degree.
2. Due acknowledgement has been made in the text to all other material used.

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Certificate

This is to certify that the Major Project entitled “**Solar Adsorption Chiller for Public Health Centres**” submitted by **Krunal K Shah (09MMET16)** towards the partial fulfillment of the requirements for the degree of Master of Technology in Thermal Engineering, Institute of Technology, Nirma University, Ahmedabad is the record of work carried out by him under my supervision and guidance. In my opinion, the submitted work has reached a level required for being accepted for examination. The results embodied in this major project, to the best of my knowledge, haven’t been submitted to any other university or institution for award of any degree or diploma.

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Acknowledgements

I am deeply indebted to Central Salt and Marine Chemical Research Institute(CSMCRI), Bhavnagar for giving me the opportunity to work here and providing me an excellent environment.

My words prove to be insufficient in thanking my guide Dr. S Maiti, Scientist, CSMCRI, without whose invaluable guidance, the completion of this report indeed have been a herculean task. The suggestions given by him were invaluable and are sincerely considered by me. I am also thankful to Dr. P K Ghosh, Director, CSMCRI, Bhavnagar,Gujarat for allowing me to carry out this work at their premises.

I would like to thank my institute guide Dr. R N Patel for their valuable guidance and encouragement throughout this period. I am very thankful to Prof. V R Iyer (Head, Department of Mechanical Engineering, Institute of Technology, Nirma University) and Dr. K.R. Kotecha (Director, Institute of Technology, Nirma University) for his kind support in all respects.

I grasp this opportunity to express my sincere gratitude to all employees in solar department as well as workshop department, CSMCRI, Bhavnagar for their tremendous support & suggestions.

Last but not the least, I would like to thank Almighty God, my parents, my family members and friends for their love, support and excellent co-operation to build my morale during the work.

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Abstract

The project aims to develop a solar adsorption chiller capable of producing 2 kg of ice with cooling capacity of 27 W. The activated carbon – methanol adsorption pair was used among other pairs such as Zeolite-Water, Carbon-Amonia, Silica gel-Water. Due to low evaporation temperature of methanol, this pair is more suitable for ice making technology.

Energy supply to refrigeration and air-conditioning system constitutes a significant role in the world. The International Institute of Refrigeration (IIR) has estimated that approximately 15% of all electricity produced worldwide is used for refrigeration and air-conditioning processes of various kinds.

Since India has different climate conditions and possess high average annual daily solar radiation, especially in summer months when there is a high demand of cooling. The daily Solar radiation on the surface of the adsorbent bed is about 15-27 MJ/m^2.

The effective exposed area of a flat plate type collector having clear plane glass sheet was calculated as 0.90 m^2. For 2 Kg of methanol, activated carbon required was 7 Kg. Two types of condensers were tested, the first one was a helical copper tube immersed in water tank and the other was a copper tube with fin. The evaporator had sufficient volume to collect the entire condensed methanol. In order to enhance the heat transfer effect in evaporator, the heat exchange surface is designed as a series of four trapezoidal cells. The experiments were done using natural solar radiation. During experiments the operating pressure was found to be an important parameter. In this study the required cooling was not observed due to loss in vacuum.

The advantage of these systems are noiseless, no maintenance cost, no moving parts, non-polluting and uses solar thermal collector, which is cheaper than photovoltaic cells.

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Chapter 1

Introduction

Everywhere in our world, refrigeration is a major energy user. In a poor area, “off grid” refrigeration is a critically important need. Both of these considerations point the way toward refrigeration using renewable energy, as part of a sustainable way of life. Solar-powered refrigeration is a real and exciting possibility.

Due to the increasing concentration of greenhouse gases and climate changes, the need for renewable energy sources is greater than ever. This has now attracted attention from the countries that has set up targets to increase the share of renewable energy supply in the world in order to reduce greenhouse gas emissions.

Energy supply to refrigeration and air-conditioning system constitutes a significant role in the world. The International Institute of Refrigeration (IIR) has estimated that approximately 15% of all electricity produced worldwide is used for refrigeration and air-conditioning processes of various kinds.[1]

The cooling load is generally high when solar radiation is high. Together with existing technologies, solar energy can be converted to both electricity and heat; either of which can be used to power refrigeration systems. Being provided with a good electricity grid worldwide, people are, however, more likely to choose a vapor compression air-conditioning system. Indian climate has an attractive potential for solar energy application. The overall aim of this study is to develop a solar powered adsorption chiller using locally available technologies. Despite the greatest effort needed to make the system sealed, the system was very simple, needs no maintenance and has no moving parts consequently it is noiseless.

1.1 Overview of Solar Cooling

1.1.1 Refrigeration Definition

In general, refrigeration is defined as any process of heat removal. More specifically, Refrigeration is defined as the branch of science that deals with the process of reducing and maintaining the temperature of a space or material below the temperature of the surroundings.

To accomplish this, heat must be removed from the body being refrigerated and transferred to another body whose temperature is below that of the refrigerated body. Since the heat removed from the refrigerated body is transferred to another body, it is evident that refrigerating and heating are actually opposite ends of the same process. Often only, the desired result distinguishes one from the other. Therefore, solar energy may be used for cooling. This is usually done by using absorption or adsorption system refrigeration. These systems require a heat source. The heat is used to drive the refrigerant out of another substance which has the opportunity to release it when they are heated and to adsorb it when be cooled. The sun can supply the heat required to operate adsorption or absorption cycles.[2]

1.1.2 Solar Cooling Path

A number of possible “paths” from solar energy to “cooling services” are shown in Figure 1.1 [3]Starting from the inflow of solar energy there are obviously two significant paths to follow, solar thermal collectors to heat or PV cells to electricity .

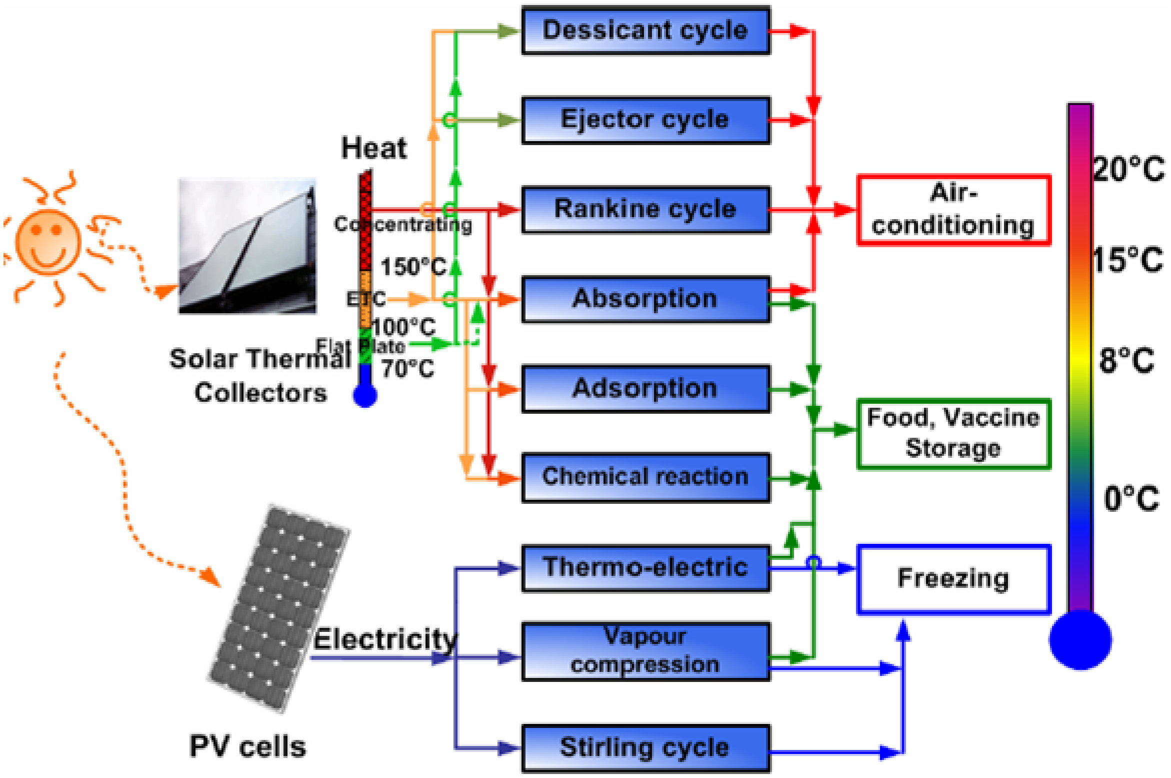


Figure 1.1: Solar Cooling Path

For solar thermal collectors, different collector types produce different temperature levels. This indicates that the temperature level can be matched to various cycle demands. For example, the Rankin cycle, requires a rather high driving temperature whereas the desiccant cycle manages at a lower temperature level of heat supply. The same type of temperature matching is important for the cold side of the solar cooling path, i.e. in the cold object. Since several cycles typically operates with water as a working fluid, it is impossible to achieve temperatures below 0°C for some cycles. The solar thermal-driven air conditioning cycles can be based on absorption cycles, adsorption cycles, duplex Rankine, desiccant cooling cycles, or ejector refrigeration cycles. When using low temperature applications for food storage at 0 to -8°C, various cycles can be applied, i.e. the vapor compression cycle, thermoelectric cycle (Peltier), absorption cycle, adsorption cycle or a chemical reaction cycle. Applications requiring temperatures below 0°C generally require small storage volumes e.g., freezing boxes. A suitable cycle for this application has proved to be the PV driven vapor compression cycle or a PV-driven Sterling cycle.[1]

1.2 Solar Cooling Technologies

The solar-driven refrigeration system, as mentioned previously, is mainly classified into two main groups depending on the energy supply : thermal/work driven system and electricity (Photovoltaic) driven system. Each group can be classified as the following :

Thermal/work driven systems

- Absorption refrigeration cycle
- Adsorption refrigeration cycle
- Chemical reaction refrigeration cycle
- Desiccant cooling cycle
- Ejector refrigeration cycle
- Rankine driven refrigeration cycle

Electricity (Photovoltaic) driven system

- Sterling refrigeration cycle
- Thermo-electric refrigeration cycle
- Vapor compression refrigeration cycle

Here we discussing about Thermal work driven system only.

1.2.1 Absorption Refrigeration Cycle

The main components of the absorption refrigeration system are an absorber, generator, a condenser, an expansion valve, a heat exchanger and a pump. The Simple diagram of the absorption refrigeration system shown in Fig 1.2. Two kinds of working medium are used at the same time in refrigeration and absorption processes. The refrigerant vapor flows to the condenser passing through a vapor-trap and condensed. Liquid refrigerant from the condenser goes through an expansion valve while the pressure is decreased to an evaporation pressure. At the evaporator, cooling effect is achieved by the vaporization of the refrigerant at a low temperature. Refrigerant vapor from the evaporator continues to an absorber and dissolves in a weak refrigerant solution, and it becomes a stronger refrigerant solution, which is called “rich solution”. A pump is the only moving part in this system. The “rich solution” is pumped to a generator. At the generator, the rich solution is heated up; the refrigerant is separated from the solution. The refrigerant is vaporized and goes to the condenser while the weak solution is passed through a heat exchanger and returned to the absorber to absorb the refrigerant vapor. The refrigeration process and the regeneration process operate at the same time as the continuous process, producing a continuous cooling effect. A flat plate solar collector can maintain the operating condition at the generation temperature about 75-100 °C but very efficient heat exchangers are required.[3]

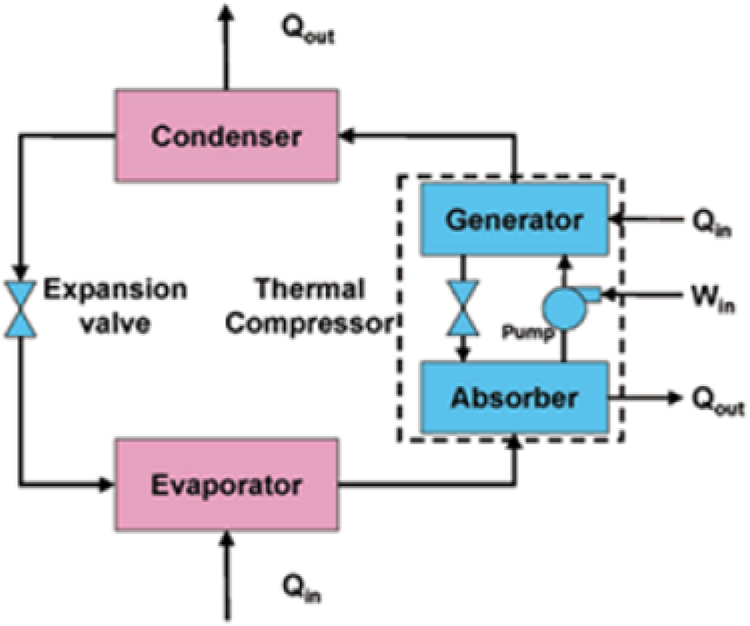


Figure 1.2: Simple diagram of absoption refrigeration system

Working Media:

Several pairs of working media have been used for absorption refrigeration system e.g. a pair of ammonia-water (ammonia is the refrigerant and water is the absorption medium), a pair of water-lithium bromide (water is the refrigerant and lithium bromide is the absorbent) and a pair of water-lithium chloride (Water being the refrigerant and lithium chloride is the absorbent). Both ammonia and water have good heat transfer characteristic. In addition, water separator (rectifier) is needed to be installed in order to prevent water from passing to the condenser with pure ammonia.

1.2.2 Adsorption Refrigeration Cycle

An adsorption, also called a solid-sorption cycle, is a preferential partitioning of substances from a gaseous or liquid phase onto a surface of a solid substrate. This process involves the separation of a substance from one phase to accumulate or concentrate on a surface of another substance. An adsorbing phase is called an 'adsorbent'. Material, which is accumulated, concentrated or adsorbed in another surface, is called an 'adsorbate'. The sticking process should not change any macroscopic form of the adsorbent except the changing in adsorbent mass.

Both adsorption and absorption can be expressed in term of sorption process. The adsorption process is caused by the Van der Vaals force between adsorbate and atoms or molecules at the adsorbent surface. The adsorbent is characterized by the surface and porosity. In the adsorption refrigeration cycle, refrigerant vapor is not be compressed to a higher temperature and pressure by the compressor but it is adsorbed by a solid with a very high microscopic porosity. This process requires only thermal energy, no mechanical energy requirement. The principles of the adsorption process provide two main processes, adsorption or refrigeration and desorption or regeneration. In case zeolite and water, as an example, the refrigerant (water) is vaporized by, the heat from cooling space and the generator (absorbent tank) is cooled by ambient air. The vapor from the cooling space is leaded to the generator tank and absorbed by adsorbent (zeolite). The rest of the water is cooled or frozen. In the regeneration process, the zeolite is heated at a high temperature until the water vapor in the zeolite is desorbed out, goes back and condenses in the water tank, which is now acting as the condenser. For a discontinuous process, the desorption process can be operated during daytime by solar energy, and the adsorption or the refrigeration process can be operated during night-time, as shown in figure1.3. The solar energy can be integrated with a generator. The single adsorber is required for a basic cycle. The number of adsorbers can be increased to enhance the efficiency, which depends on the cycle. This process can also be adapted to the continuous process.

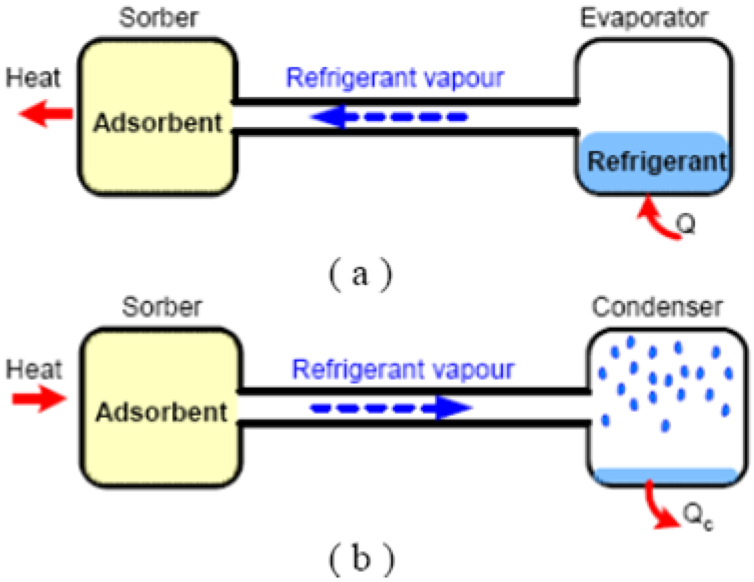


Figure 1.3: (a) The adsorption (Refrigeration) process and (b) The desorption (Regeneration) process

Working Media:

Typical and commercial adsorbents are made from silica gels, zeolite and activated carbons. The adsorbate (refrigerant fluid) could be water, ammonia or methanol. The famous pairs that have been used commercially are zeolite‘13x’/H2O for the temperature above 0 °C and activated carbon /methanol for the temperature below 0 °C.The others are ammonia/SrCl2, water/silica gel or air/silica gel in the open cycle.[1]

1.2.3 Chemical Reaction Refrigeration Cycle

A chemical reaction refrigeration cycle is a solid-gas adsorption process with a chemical reaction. It is an intermittent system. The principle of chemical reaction solid-sorption process is similar to the adsorption process. The same analogies of these two systems are:

- They are intermittent processes since the cold cycle is not continuously produced.

- They are heat-driven refrigeration cycles (The mechanical work is required in some cases to blow out the vapor). The sorption latent heat from the gas phase is the driving energy.

Table 1.1 Shows Comparisons between Physical and Chemical Adsorption Refrigeration Cycles

Table 1.1: Comparisons between Physical and Chemical Adsorption Refrigeration Cycles.

The main different properties	Physical Adsorption	Chemical Adsorption
Forces Causing the Adsorption Process	The physical adsorption process occurs due to van der Waals force. This force bind the adsorbing molecules to the solid phase.These adsorption process on the surface of the adsorbent does not cause deformation or changes any macroscopic structure of the adsorbent(solid).The binding molecules can be released by applying heat.	The chemical adsorption process occurs due to covalent or ionic bond.The adsorbent and the adsorbate share electrons between each other and form a complex surface compound.The forces of these bonds are much stronger than the Van der Waals force.
The Thermodynamic operation of the cycle	The physical adsorption is a reversilble process. To complete the adsorption and desorption cycle, heat supplied is required to the adsorber to increase the temperature of the adsorbent	The chemical adsorption process is very difficult to reverse.To complete the cycle, more heat supply to the adsorption cycle is required to achieve high kinetics of reaction.
The Working Media	Several pairs can be used e.g. - Activated carbon/Amonia -Activated carbon/Methanol - Silicagel/Water - Zeollite/Water	There are two main groups of working pairs: Amonia salts with alkaline compounds e.g. BaCl2,MnCl2,etc.Hydrogen and Methalhydrides with low hysterisintermetallicor meshed metal compounds e.g. LaNi5

1.2.4 Desiccant Refrigeration System

A desiccant cooling system is based on an open-cycle dehumidification process. Heat and water are needed to operate this system. Water is commonly used as a refrigerant since it is cheap and environmentally friendly. A desiccant material can be either liquid or solid. This cycle consists of one drying process, one heat exchanging process and one humidifying process. There are three major components, operating in an atmospheric pressure. These components are a dehumidifier, an evaporative cooler and a regenerator. Heat exchangers are also used as the additional components to increase the system efficiency. A drying process can be performed in a desiccant wheel when solid desiccant (such as silica gel or zeolite) is used, or it can be performed in an absorption tank when liquid desiccant is used. A heat exchanging process occurs in a heat exchanger and the humidifying process is performed in a saturated pad or humidifier. The rotor wheel is widely used as the heat exchanger wheel and the drying wheel. A simple diagram is shown in figure 1.4.[3] Outdoor air is dehumidified with a solid or liquid desiccant where some of the moisture is removed, resulting in rising of the air temperature and decreasing of the humidity. The air is then cooled by exchanging sensible heat to the returned air in the heat exchanger and humidified to the desired humidity before supplied to the cooling space. The temperature of the supply air is further lowered by the humidifier or the evaporative cooler before entering the cooling space. The returned air from the cooling space is returned to the evaporative humidifier. It is humidified to a lower temperature at the same enthalpy but with a higher humidity. The cooled air enters the energy recovery unit where acting as the cooling medium for the supply air. The air temperature is increased after passing the heat recovery (heat exchanger wheel). It is then passsed through a heater, where it is further heated, and then enters the reactivation sector of the desiccant rotor to reactivate the desiccant.

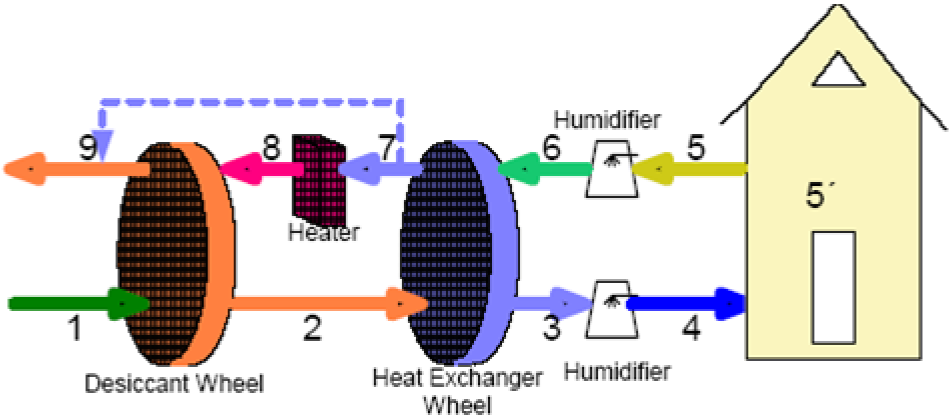


Figure 1.4: Solid Desiccant Cooling Machine

The wet air leaves the rotor as the exhaust air. This process is shown in the Mollier's diagram in figure 1.5 . The energy supply to the heater depends on the temperature of the return air entering the desiccant wheel at stage 8. The humidity of the entering air and the effectiveness of the desiccant affect the amount of energy supply.

The low-temperature heat can be supplied to the heater such as solar energy from flat plate solar collector, waste heat from industry or geothermal energy. A small amount of electricity is required for rotating the wheels. The desiccant materials for a solid-desiccant system are usually silica gel or Zeolite. For a liquid desiccant system, the desiccant dehumidifier's hygroscopic aqueous solution can be triethylene glycol (TEG), CaCl2-H2O, LiBr-H2O, LiCl-H2O etc.

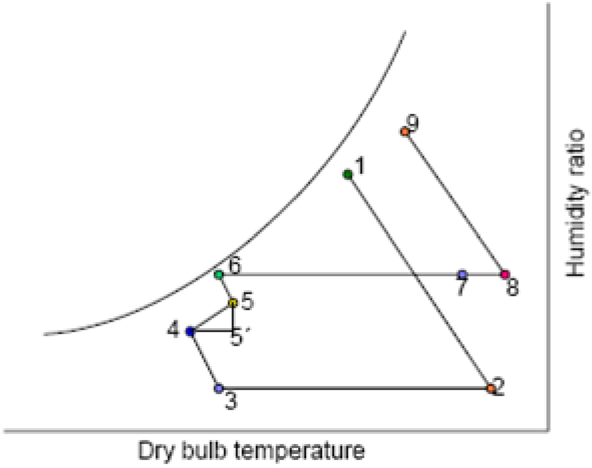


Figure 1.5: Dessicant cooling process

1.2.5 Ejector Refrigeration Cycle

An ejector refrigeration cycle is one of the heat-operating cycles Fig. 1.6 The interesting advantage is as a 'low temperature heat supply' air conditioning system. With this outstanding, the research and development of such a system has been considered increasingly since the energy crisis 1970s. Solar energy (as a renewable source) and waste heat from a heat operated process such as from truck engines can be integrated with the ejector refrigeration system. The simplicity in installation, design and operation are advantages. The pump is the only moving component in this system. The ejector and the pump are used to maintain the pressure differences in the system. Low efficiency is a drawback of this system, however when the generating temperature is low, the COP of the ejector cycle is higher than the corresponding COP of an absorption system; moreover low-graded heat can be applied.

The major components in the solar-driven refrigeration system are an ejector, a condenser, a generator, an evaporator, an expansion device and a pump. The vapor from the low temperature evaporator is sucked into the high velocity vapor stream in the ejector. The high velocity vapor stream goes through a converging-diverging nozzle in the ejector resulting in the vapor being sucked from the low temperature evaporator. The suction occurs, as the pressure is low at the narrowest section of the ejector. The stream from the evaporator reaches subsonic velocity. A mixing occurs in a mixing zone at the end of the converging section.

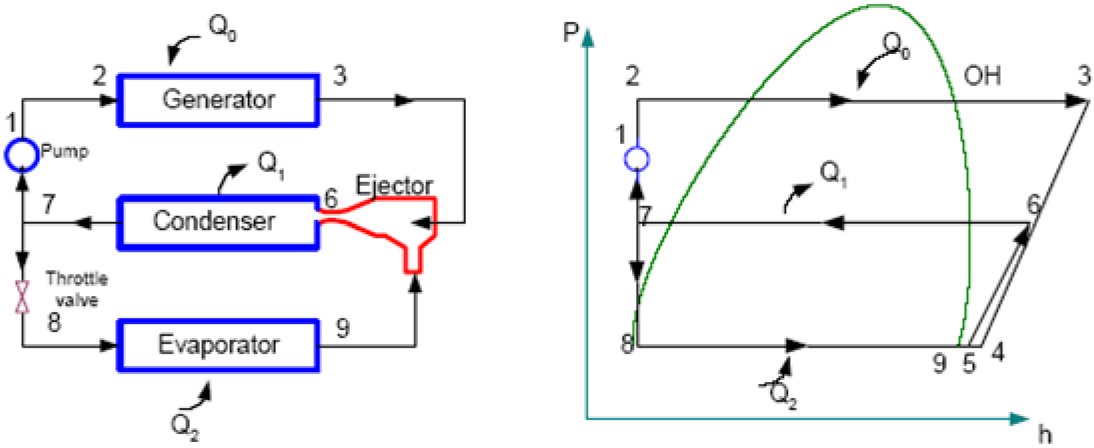


Figure 1.6: Ejector Refrigeration Cycle

After mixing, a combined stream becomes a transient supersonic stream, and the velocity of the combined fluid must be high enough to increase the pressure after deceleration in the diffuser to a suitable condensing pressure. After the pressure build-up, the stream from the ejector goes to the condenser, condenses and heat is rejected to the environment. After the condenser, one part of the fluid is pumped to the generator and the rest goes to the evaporator, reaching the evaporating pressure through the expansion device. Many refrigerants can be used with an ejector refrigeration system such as water, R113, R114, R141b, R134a, R11 and R12.

1.2.6 Rankin-Driven Refrigeration Cycle

A Carnot heat engine is the most efficient engine to produce work from heat. Heat in the Carnot engine transfers from a higher temperature to a lower temperature.

Generally, the Carnot heat engines cannot be operated since the mechanical problems such as erosion or cavitations of turbine blades, when operating in a two-phase region.

The adaptation of the Carnot heat engine in the one-phase region is called “Rankin" cycle. The reversible of the Rankin heat engine is called the ‘Rankin refrigeration cycle’ or the ‘vapor compression cycle’. Work from the turbine of the power cycle drives the compressor of the refrigeration cycle. Any excess energy can be used to produce electricity and reserved as a backup energy when sunshine is lacking or it can be connected to a grid system, figure 1.7.[1]

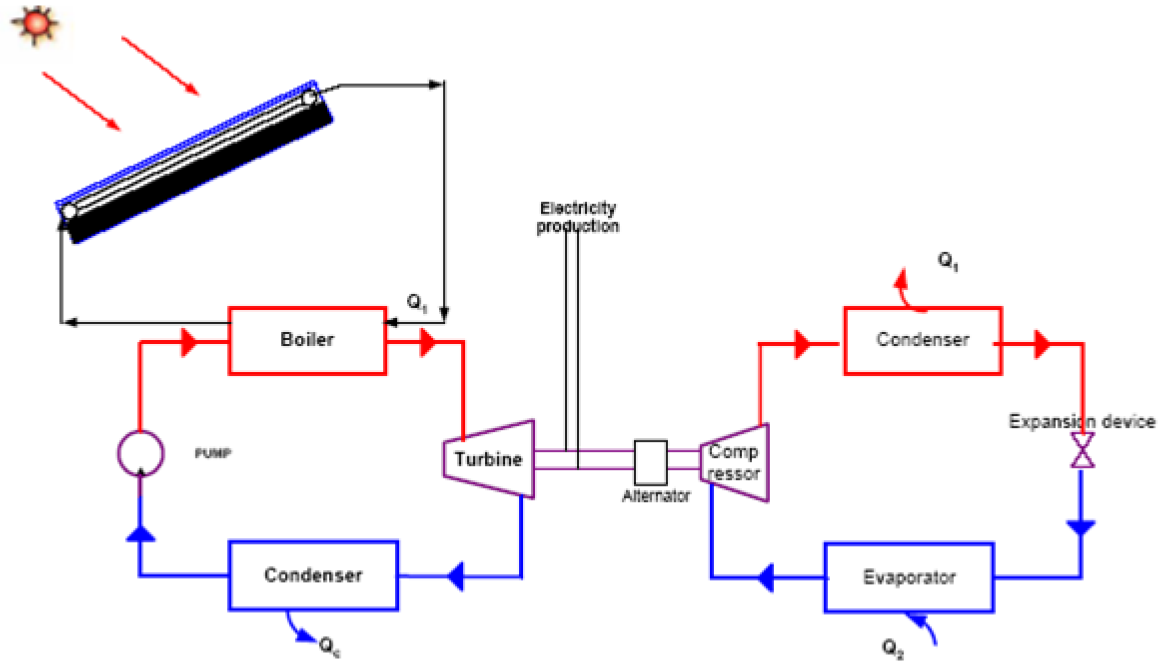


Figure 1.7: Solar Driven Rankine Cycle

A solar-operated Rankine cycle is not much different from a conventional power plant, using water as the working fluid. To increase the efficiency and prevent the erosion of the turbine blades, superheating and extraction processes are used. The working fluid in the Rankin power cycle and the refrigeration cycle can be different. The suitable refrigerant in the solar operating system should be chosen to avoid moisture in a turbine. Superheating is not preferred since the increasing of the collector temperature requirement. The extraction is not economic for a small system. Working fluids such as R114 that give a positive slope of the saturated vapor line on a T-S diagram, the outlet temperature from the turbine is significantly higher than the condensation temperature gives the benefit to preheat the working fluid before it enters the boiler. However R114 is not environmental friendly; it has an ozone depleting potential due to a Chlorine atom.

The speed of the turbine and the compressor should be analogous. The alternator or other equipment that used to adjust the speed should be installed with the system.

Chapter 2

Literature Review

In the literature, there are many experimental studies on adsorption systems. Only the studies that are related to the present study are chronologically summarized here for brevity. Interested readers may refer to the provided references for more information for each study.

2.1 History

In the early years of the previous century, sorption (adsorption) refrigeration was frequently used, later with the development of cheap reliable compressors and electrical motors, the improvement in power station efficiency and the introduction of CFCs in the 1930s, sorption refrigeration became a niche technology.[5]

Heat-driven sorption refrigeration cycles have existed in patent literature since at least 1909, and refrigerators were commercially available in the 1920s. In 1929, Miller described several systems, which utilized silica gel and sulfur dioxide as an adsorbent/adsorbate pair.[6] However, recent years have witnessed increasing interest in this technology for many different reasons. The main arguments in favor are that sorption systems are quiet, long lasting, cheap to maintain and environmentally benign.

Refrigeration technology is required to evolve due to the new environmental regulation. The first regulation concerning the depletion of the ozone layer (Montreal protocol, 1988) [7], decided to phase-out chlorofluorocarbons (CFCs) and then hydro chlorofluorocarbons (HCFCs). More recently adsorptive processes have been proposed for heat pump and refrigeration as consistent alternative to vapor compression systems. Ecological problems concerning the emission of CFCs from refrigerating units have stimulated several theoretical and experimental studies on adsorption cooling systems. The environmental impact of fluorocarbon traces in the atmosphere has shown that CFC emissions are responsible for about one-third the global greenhouse effect.[8]

These trends bring to a strong exigency of new systems for space heating and cooling, with the possibility also to obtain a primary energy diversification. Among the proposed technologies, the solid sorption has a very good perspective, in fact, in addition to the non-polluting refrigerants, they can efficiently use natural gas or solar energy as primary energy and they have no moving parts, which makes the machine silent and with no maintenance needs. Therefore, adsorption heating and cooling can be a good alternative to classical vapor-compression machines. Adsorption cooling units are attractive since they can be operated at temperature levels where liquid absorption systems cannot work.

One of the earliest studies which can be accessible on solar adsorption systems was performed by Pons and Guilleminot in 1986.[9] A solar powered adsorption ice making system was analyzed from the fall 1984 to the end of summer 1985. Activat-ed carbon – methanol pair was selected, the maximum bed temperature was 95 $°C$ and the evaporation temperature varied between -5 $°C$ and -10 $°C$. A maximum COP of 0.15 for the system was obtained.

Another study was performed by Wang et al. in 1998.[10] As stated in this study, the most important parameters that affect the cycle performance are the cycle time and maximum bed temperature for a simple adsorption cycle. This study investigated these two parameters and compared experimental values with the simulated model results.

Wang in 2001 investigated the effects of heat and mass recovery on the simple cycle with two adsorbent beds and activated carbon – methanol pair.[11] The experimental results stated with the addition of heat recovery, the COP values increased by approximately 25%. Implementing mass recovery before heat recovery added 10% to the COP value of a simple cycle with heat recovery. Results also showed that with the mass recovery after heat recovery, COP reached 0.5 for a maximum bed temperature of 100 $°C$, condensation temperature of 24 $°C$, evaporation temperature of 10 $°C$.

A prototype of a solar powered simple adsorption cooling system was built in Nigeria by Anyanwu and Ezekwe in 2003. This designed system was tested with activated carbon-methanol pair. The useful cycle and the useful overall COPs ranged over 0.056–0.093 and 0.007–0.015, respectively.

Thus, the maximum of only 10% of the collected energy by the activated carbon granules and 2% of the incident solar energy were converted to the refrigeration effect. In this experiment Only chilled water was produced, so far, at temperatures of around 1 $°C$. Drugs, fruits and vegetables with preservation temperatures in the range 4–16 $°C$ are within the scope of the present system.[12]

A solar adsorption ice maker with activated carbon–methanol adsorption pair was developed for a practical application by Wang in china in 2004. Test results show that the COP (coefficient of performance) of the solar ice maker is about 0.083–0.127, and its daily ice production varies within the range of 3.2–6.5 kg/m^2 under the climatic conditions of daily solar radiation on the surface of the adsorbent bed being about 15–23 MJ/m^2 and the daily average ambient temperature being within 7.7–21.1 $°C$. The suitable daily solar radiation under which the solar ice maker can run effectively in Kunming is above 16 MJ/m^2.[13]

2.2 System Description

One of the very effective forms of solar refrigeration is the production of ice, since ice accumulates much latent heat in it. The most promising application to produce ice by using solar energy is the solid adsorption refrigeration, due to its simple operation and its ability to utilize low grade thermal energy. Although different adsorption pairs had been studied to build adapted solar ice maker. The activated carbon–methanol pair was found the most suitable for solar-powered refrigeration.[14] The adsorption solar refrigerator in its simplest form is a closed system composed of the container of adsorbents and adsorbate (sorption bed), which serves as a solar collector, a condenser and an evaporator. The cycle of this system is divided into two periods: First, the adsorbent is heated by solar energy during the day and the desorbed adsorbate is condensed. Then the adsorbent is cooled after sunset, thereby re-adsorbing the adsorbate, the evaporation of which produces the refrigeration effect. As desorption is highly endothermic, the heat input to the adsorber must be large enough to allow for sufficient refrigerant to be desorped. On the other hand, adsorption is highly exothermal, so, cooling down of the adsorber is also a major concern. Although, the alternation of heating and cooling during the cycle perfectly suits the intermittent nature of solar energy, yet efficient operation of the system requires high rates of heat transfer in and out of the adsorbent. Unfortunately, some problems are encountered which affect rates of heat transfer. First, the heat transfer of adsorbent bed is very poor, due to low convective heat transfer to the adsorber and bad thermal conductivity of the adsorbent. Second, the thermal mass of the container presented an unacceptably high thermal load which affected alternation of heating and cooling. Third, the system suffers from the problem of being tightly sealed against air leakage through the joints and valves which results in degrading the cooling performance. In addition, all solar systems usually suffer from the large variations in ambient conditions between winter and summer, which makes these systems inefficient for part of the year. In solar adsorption systems, while good heating is attained during day time in summer, cooling during night by ambient air will be limited. On the other hand, in winter, the system will attain good cooling during the night, but heating will be insufficient. In the last two decades, different approaches have been developed to improve heat transfer rates and enhance heating and cooling of the adsorbent bed. The use of composite adsorbent blocks and monolithic carbon are useful methods to increase both thermal conductivity and density of the bed.[16] To enhance heating of the beds, flat plate solar collectors with selective surfaces, evacuated tubular collectors and simple concentration non-tracking collectors as compound parabolic concentrator collector have been used. As cooling of the adsorbent is by rejecting heat to the environment, heat loss from the collector to the ambient could be enhanced by means of removable insulation, flaps, or dampers. Some designs combine the collector and finned condenser at one unit since outside fins have been located on the rear surface of the collector.[17] By day the solar collector is a desorber and a condenser. At night, the condenser cools the collector. Therefore the investigations must be focused to improve heat transfer in the adsorbent bed, thereby increasing COP, and to improve external heating and cooling of the bed all year round, thereby realizing good performance of the system for most times of the year.

2.3 Principle of Adsorption

Adsorption is a solid sorption process where the binding forces between fluid molecules and the solid medium come from an electrostatic origin or from dispersion - repulsion forces (Van der Waals forces). It is an exothermic process due to the gas-liquid phase change. The energy liberated in adsorption is called isosteric heat, and it depends on the nature of the adsorbent - adsorbate pair.

To describe the thermodynamic equilibrium of adsorption, several state equations known as isotherms of adsorption are proposed. These functions correlate the temperature T, the pressure P, and the concentration of the adsorbed phase a , so that f (T, P, a) = 0, [21]. The main isotherms of adsorption are: (a) Henry's law, valid for weak concentrations; (b) Langmuir's approach, which considers adsorption in monomolecular layers and that there is a dynamic equilibrium between the phases;

(c) Gibbs' theory, based on the perfect gas equation, in which the adsorbate is treated in microscopic and bidimensional form; and (d) Adsorption Potential theory, based on a model originally proposed by Polany by the end of the 20s, which is a purely thermodynamic approach, suitable for adsorption in micro porous materials. A detailed analysis of the thermodynamics of adsorption and its different isotherms is given by Leite.[18]

All micro porous materials are generally adsorbent media, characterized by high porosity. Their structures have pores with diameters smaller than 20A . The most commonly utilized adsorbents are silica gel, activated carbon, alumines and zeolites. Zeolite-water and activated carbon- methanol are the most used adsorbent-adsorbate pairs in refrigeration systems. These two pairs have entirely different physical and chemical properties: methanol is easily desorbed from activated carbon when it is heated, while in zeolite, the water is kept much longer. Thus, the activated carbon methanol pair is best adapted to operating cycles with small evaporating temperature, since adsorption cycles with the Zeolite+water pair need a larger evaporating temperature change to operate.[19]

For the equilibrium of adsorption in micro porous materials with a polymodal distribution of pore dimensions, such as the activated carbon/methanol pair, Dubinin and Astakhov [20] proposed the following isotherm:

$$a = W_o \rho_1(T) \exp\{-D[T \ln(p/P_s)]^n\}$$

where, a, is the adsorbed mass per unit of adsorbent mass, W_o the maximum adsorption capacity (volume of adsorbate/mass of adsorbent), $\rho_1$the specific mass of the adsorbate in the liquid state, D the coefficient of affinity and n is a characteristic parameter of the adsorbent/adsorbate pair.

This equation has a wide field of application, and it is particularly appropriate strongly for activated carbon with a large pores heterogeneousness. According to [21], a fitted curve obtained from experimental results of methanol adsorption in activated carbon presented a residual error of 2.2%, related to the characteristic function proposed by Dubinin and Astakhov. These experiments were performed within a temperature range between 20 and 100 °C and for an adsorbed mass ranging from 71 to 286 g/kg of adsorbent. For smaller temperatures, the residual error was lower than 2%. These results indicate that this state equation is possibly adequate for many engineering applications of low grade heat, especially those concerning solar energy.

2.4 Selection of Adsorbent / Adsorbate Pair

At present, three types of working adsorate and adsorbent, respectively, are favored for pairing for use in solid adsorption solar refrigeration technology: Ammonia, Methanol and Water for adsorbate and activated carbon, silica-gel and zeolite for the adsorbent. The selection of any pair of adsorbent/adsorbate depends on certain desirable characteristics of their constituents, including the affinity for each other. These characteristics range from their thermodynamic and chemical properties to their physical properties and even to their costs or availability.

For refrigerating applications, "the adsorbent must have high adsorptive capacity at ambient temperature and low pressures and a small capacity of adsorption at high temperatures and pressures". The cooling effect, or the temperature attained in the evaporator, depends on the adsorptive capacity at small pressures. This is the property that allows the adsorbent, at a given temperature, to retain vapors from a fluid at a lower temperature. On the other hand, the more intense this property is, the higher the adsorbent regenerating temperature. Thus, choosing the adsorbent will depend on two basic factors:

- The temperature at which the evaporator must operate.
- The regenerating temperature that the thermal source can possibly attain.

Another important aspect in choosing the adsorbent is the possible catalysis of the adsorbate's dissociating reactions. For example, the methanol adsorption in zeolite is restricted to 100 °C as its maximum temperature. At higher values, the zeolite is a catalyst for the methanol, water and dimethyl ether reaction, producing a blockage of the adsorption process [5]. For the activated carbon-methanol pair, this catalyst reaction will only occur above 150 $°C$, which is perfectly suitable for solar refrigeration applications. Thus we can summarize the considerations influencing the choice of a suitable adsorbent as follows :

- Porous materials that should adsorb a large amounts of the adsorbate under low temperature conditions to yield good COP.
- Desorption of most of the adsorbate when exposed to thermal energy.
- Possession of high latent heat of adsorption compared to its sensible heating load.
- No deterioration with age or use, thus it is reversibility of adsorption process for many cycles.
- Non-toxic and non-corrosive.
- Low cost and widely available.
- Wide concentration change in a small temperature range.
- Good thermal conductivity.

The choice of the adsorbate, or the working fluid, shall depend on the main conditions:

- The evaporator temperature, according to the application.
- The latent heat of evaporation, which should be high.
- The molecular dimensions, which should be small enough to allow easy adsorption.
- Thermally stable with the adsorbent at the cycle operating temperature ranges.
- Non-toxic, non-corrosive and non-flammable.
- Low saturation pressures (slightly above atmospheric) at normal operating temperature.

A survey of the favored working adsorbates shows that methanol and water operate at subatmospheric saturation pressures at the operating temperatures needed, and an ingress of air immediately results in system malfunction. Ammonia does not have this problem because its outward leak could be tolerated for some time, but its saturation pressure of 13 bar at 35 $°C$ condensing temperature is quite high. In the case of methanol, with a normal boiling point of 65 $°C$, the low saturation pressures could be exploited advantageously to detect leakages, since it must necessarily result in abnormal increases in system pressure and poor performances.

Ammonia, methanol and water, all have relatively high latent heat values of 1368, 1102 and 2258 kJ/kg, respectively, and their specific volumes are low, on the order of about 10^{-3} m^3/kg [22].

Ammonia is toxic and corrosive, while water and methanol are not, but the problem with alcohols is that they are flammable. Water is the most thermally stable with adsorbents, closely followed by methanol and ammonia in that order. However, water cannot be used for freezing purposes because its freezing temperature is 0 $°C$. This makes methanol a favored adsorbate for pairing with a stable adsorbent.

Various kinds of working pairs for adsorption refrigeration have been already studied, and they include both physical and chemical adsorption working pairs. The main physical adsorbents are activated carbon, zeolite, and silica gel, and accordingly, the physical adsorption working pairs are mainly activated carbon–methanol, activated carbon– ammonia, zeolite–water and silica gel–water. In recent years, the working pairs activated carbon–HFC-134a, and activated carbon–dimethylether were also investigated.[23]

As water is the refrigerant normally used with zeolite or silica gel, the evaporating temperature is never lower than 0 $°C$. Compared to other physical adsorption working pairs, the main advantage of the utilization of activated carbon as adsorbent is the low evaporating temperature that can be reached, as the refrigerants most employed are ammonia or methanol. Due to the low evaporation temperature of these refrigerants, these pairs are more suitable for ice making technology.

Chemical adsorbents mainly include metal chlorides and metal hydrides. The metal chlorides generally use ammonia as refrigerant when designed for ice making pur-

Table 2.1: Differential heats of adsorption for some adsorbent/ adsorbate pairs.

Adsorbent	Adsorbate	Heat of Adsorption (KJ/Kg)	Density of the adsorbate (Kg/m^3)	Application area
Activated alumina	H_2O	2800	1000	Used mostly for desiccant cooling
Zeolite(Various grades)	H_2O NH_3 CO_2 CH_3OH	3300-4200 4000-6000 800-1000 2300-2600	1000 681 - 791	Natural zeolites have lower value than synthetic zeolites
Silica gel	Methyl alcohol	1000-1500	703	Not suitable above 200 $°C$
Charcoal (Activated carbon)	C_2H_4 NH_3 H_2O CH_3OH C_2H_5OH	1000-1200 2000-2700 2300-2600 1800-2000 1200-1400	789	Used for coolig. coolig. Reacts above 150 $°C$.

poses. The main advantage of the metal chlorides working pairs is the larger adsorption quantities, which are about 5–6 times of that obtained with the physical adsorption working pairs.

The disadvantages of metal chlorides are the phenomena of swelling and agglomeration when the expansion space for the salt is, respectively, too large or too small. The swelling phenomenon reduces the heat transfer performance, and the agglomeration phenomenon reduces the mass transfer performance. In order to improve the heat and mass transfer of metal chlorides, composite adsorbents using graphite or carbon fiber as porous additives were researched. Various studies have developed detailed models and examined the suitability of various adsorbent/adsorbate pairs for solar cooling applications.[23] Differential heats of adsorption for some adsorbent/adsorbate pairs are given in Table 2.1.[7]

The Dubinin–Astakhov (D–A) equation can also be employed to evaluate the desorption/adsorption capacity of the activated carbon, this equation can be written in the form [24]:

$$x = x_o \exp[-K(T/T_s - 1)^n]$$

Where x_o, K, and n are coefficients specific for different activated carbons and refrigerants, T is adsorption temperature (K), T_s is the saturated temperature of refrigerant (K), and x is the adsorption quantity of refrigerant in the activated carbon (kg/kg).

Adsorption properties of activated carbon–methanol were tested, and the coefficients of D–A equations are: x_o= 0.45; K = 13.38; n = 1.5.

The cooling quantity is the product of latent heat and the adsorption quantity. The values of latent heat for ammonia and methanol are similar. For example, at the evaporating temperature of -30 $°C$, the latent heat of ammonia is 1365 kJ/kg , which is only 5% larger than the value of methanol that is 1299 kJ/kg. The adsorption quantity of activated carbon–methanol is 59% larger than that of activated carbon–ammonia, which means that the adsorption performance of activated carbon–methanol is better than that of activated carbon–ammonia.[24]

The temperature lift capabilities of adsorbent/adsorbate pairs [22], which are adsorption– evaporation and generation–condensation temperatures, have been used as the basis for their selection.

Activated carbon/ methanol are limited to a maximum generating temperature of 150 $°C$ due to methanol instability at higher temperatures. This feature of the pair makes it possible for low temperature heat sources to be used in the operation of its refrigeration cycle.

There are other reasons that make the activated carbon/methanol pair more attractive for use in solar cooling systems. Consolidated activated carbon bed is an effective way to improve the heat transfer performance of granular activated carbon. Activated carbon grains are consolidated by mixing and compressing them with a binder. The thermal conductivity of granular and consolidated activated carbons was measured according to [23], by a transient hot wire method, which had an estimated maximum error of ± 8%. When compared to granular carbon, the density of consolidated activated carbon has been improved by 30%, and the thermal conductivity has been 172% higher.

After the above arguments and considering the cooling adsorption system purpose, which is ice production, the activated carbon-methanol pair seems to be very adequate. Methanol is a good working fluid because[14]:

- It can evaporate at a temperature largely below 0 $^{\circ}C$ (its melting point is -94 $^{\circ}C$).
- Its latent heat of evaporation is signigicant (about 1100 KJ/Kg), so the cycle COP could reach a higher value.
- Its molecule is so small (4 $^{\circ}A$), it can be easily adsorbed in microspores with a diameter smaller than 20 $^{\circ}A$.
- Its normal boiling point (65 $^{\circ}C$) is much higher than room temperature.
- Its working pressure is always lower than atmospheric. This is a safety factor because any abnormal behavior of the machine can be detected before methanol leaks from the system.

Activated carbon has a significant volume of microspores of convenient size for adsorption. The void space in the activated carbon adsorbent bed corresponds to 78% of its total volume, and the microspores volume is about 0.4 L/Kg[21]. Activated carbon present some additional characteristics such as wide concentration change in a small temperature range, reversibility of adsorption process for many cycles, and low cost.

2.5 Operation and Analysis of the Adsorption Cycle

The operation principle of the solid adsorption refrigeration system utilizing solar heat is shown in Fig. 2.1.[15] The system is composed of a container of adsorbents, which serves as a solar collector, a condenser and an evaporator which acts as a refrigerator. A combination of adsorbent and adsorbate is confined in a closed system where no carrier gas exist. The collector is supplied with activated carbon (A.C) which is adsorbed with methanol. During the day-time the activated carbon along with the methanol is heated in the collector. Methanol evaporates from the activated carbon and then is cooled by the condenser and stored in the evaporator.

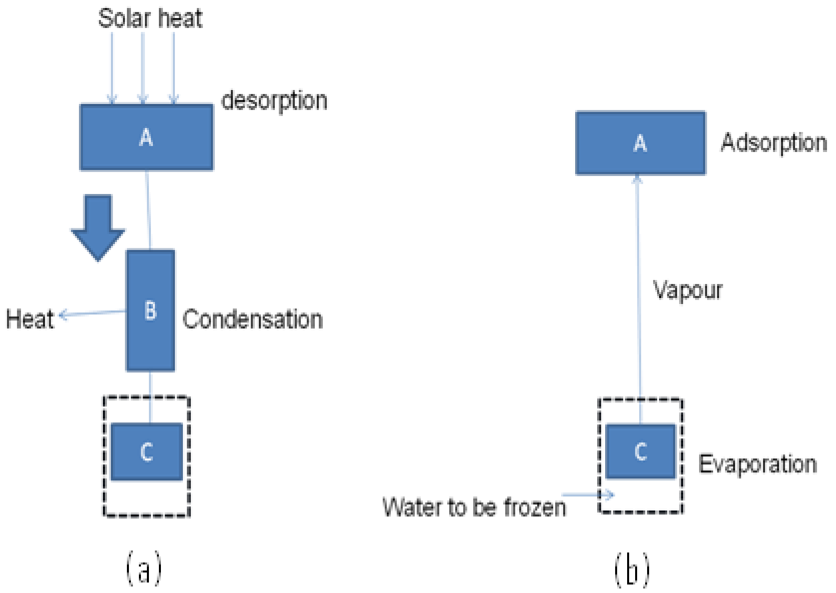


Figure 2.1: Operation principle of solid adsorption refrigeration system utilizing solar heat A: Solar collector; B: condenser; C: evaporator. (a) Daytime (heat/desorption) (b) Night-time (evaporation-adsorption)

During the night-time, the collector is cooled by ambient air and the temperature of the activated carbon reaches a minimum. In this period, methanol begins to evaporate by absorbing heat from the water to be cooled and is adsorbed by the activated carbon. As the evaporation of the methanol continues, the water temperature decreases until it reaches if possible 0°C, where ice starts to be formed. The principle of the solar adsorption chiller is explained using a Clapeyron diagram (lnP versus -1/T). Fig.2.2 shows the idealized process undergone by activated carbon + methanol in achieving the refrigeration effect.[15] The cycle begin at a point A where the adsorbent is at a low temperature T_A and at low pressure P_e (evaporator pressure). During the daylight, AB represents the heating of activated carbon along with methanol. The progressive heating of the adsorbent from B to D causes some adsorbate to be desorbed and its vapor to be condensed at the condenser pressure P_c. When the adsorbent reaches its maximum temperature T_D, desorption ceases. Then the liquid methanol is transferred into the evaporator. During night, the decrease in temperature from D to F induces the decrease in pressure from P_c to P_e. Then the adsorption and evaporation occur while the adsorbent is cooled from F to A. During this cooling period heat is withdrawn both to decrease the temperature of the adsorbent and to withdraw adsorption heat.

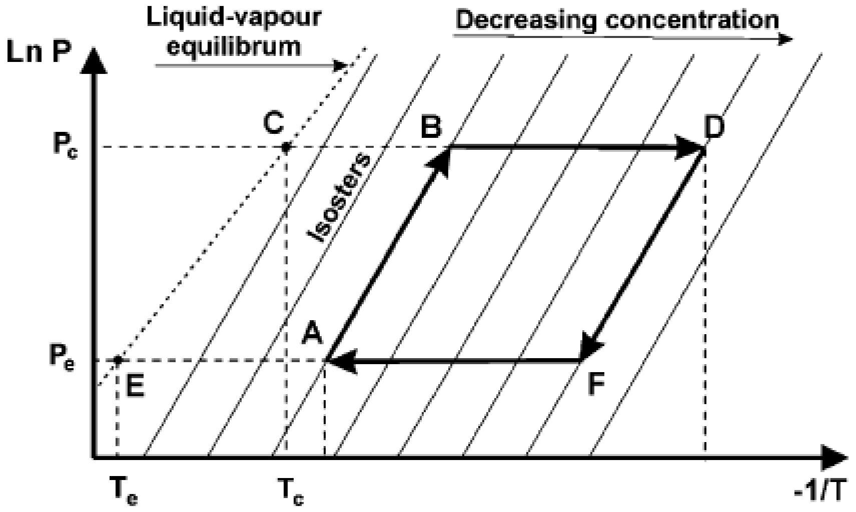


Figure 2.2: Claperyon-diagram of ideal adsorption cycle

2.6 The Effects of Collector and Environment Parameters on the Performance of a Solar Powered Adsorption Refrigerator

The characteristics of solar cooler are affected by many parameters. Generally speaking, we can divide these parameters into two types. One type is the parametric parameters, such as dimensions, material and characteristics of collector, which decides the physical property of collector. Another type of parameters is environmental parameters, such as radiation intensity, ambient temperature and wind speed, which affect the running quality of system performance.

2.6.1 Parametric Effects

As mentioned above, the characteristics of solar refrigerator are mainly decided by adsorbent bed (collector), so the property of the each collector part determines the behavior of the solar refrigerator in practical application. The solar collector design parameters of interest are the collector plate material and emissivity, the size of housing adsorbent, fins for heat transfer, material, number of glazing, the thermal conductivity, packing density of the adsorbent granules. The performance of solar refrigerator is mainly decided by the total condensed refrigerant, the cooled water, the produced ice mass if possible as well as the useful coefficient of performance (COP). The latter is defined as the total useful cooling divided by the total incident radiation. In the processes of analyzing parametric effects on the solar refrigerator, the environmental conditions assumed remain constant.[25]

Effect of Heat Transfer Fins

Because the thermal conductivity of the adsorbent is low, using fins to improve heat transfer is very important inside the collector adsorbent. Theoretically speaking, increasing the number of fins will improve heat transfer, but it is obvious that the presence of these fins also has negative effects, because the sensible heat of the fins will be thermodynamically useless. So there is an optimization value about the fin numbers.

Effects of the Contact Thermal Resistance

The contact thermal resistance is a key parameter which affects the characteristics of solar refrigerator. The adsorbent is installed usually inside definite shape of metal, the metal accepts the solar radiation energy to heat adsorbent to release refrigerant.

Due to the existence of thermal contact resistance between adsorbent and metal surface, this will lead a big temperature gradient and reduce the heat transfer effect from metal surface to adsorbent. Usually, the bigger the contact thermal resistance between metal surface and adsorbent, the inferior is the characteristics of solar refrigerator. Therefore, in order to reduce this contact thermal resistance, a well suited shape of the solid bed with a smooth surface should be taken into consideration carefully.

Effects of Adsorbent Thermal Conductivity

Nearly all suitable adsorbents are porous materials that can adsorb a large amount of refrigerant, while the thermal conductivity of the adsorbent is very low, this makes limiting factor to performance of solar cooler. For flat plate solar refrigerator, activated carbon is usually chosen as adsorbent, and the thermal conductivity values of adsorbent are usually less than 1.0 W/m-K . So it is very useful to pay attention to improve the heat transfer in adsorbent bed. In order to improve the adsorbent conductivity, many methods have been adopted.[26] For example, metallic spheres or strips can be incorporated into the bed, or good thermal conductivity material or metallic foam can be used to the absorbent, and consolidated samples (like bricks) is used. But so far, there are no practical application used in solar refrigerator.

Effect of Number of Glazing and Selective Coating

Besides the above mentioned parameters, there are many other parameters that affect the performance of solar refrigerator and ice mass, such as numbers of glass cover, coating material etc. Among these parameters, two parameters are most important; they are the number of glazing and the selective coating material. Usually, the increase of glazing number is limited by collector structure and dimension; in common practice, not more than two or three glazing. In summary, many parameters affect the characteristics of solar refrigerator. From the view of optimization of design, we should choose the best parameter to build the collector under the suitable cost.[4]

2.6.2 Environmental Effects

When a collector has been built and connected with condenser, charging valve and evaporator, the solar refrigerator device is fabricated. After considering the parametric effects on design of collector, the solar refrigerator properties of COP and water will be cooled are mainly decided by environmental parameters, such as condensing temperature, evaporating temperature and solar radiation intensity. So discussing environmental parameter variation effects on the characteristics of solar refrigerator must be studied.

Effects of the Solar Radiation Intensity

Solar refrigerator is powered by solar radiation energy, so the solar radiation intensity decides the water temperature as well as the COP value. The COP of solar refrigerator increases with the increase of solar radiation intensity first. However, with the increase of solar intensity, the value of COP does not increase synchronously, conversely the COP of solar system decreases by some degree. This reason can be explained as follows: solar radiation intensity is used for both adsorbent sensible heat and metallic sensible heat. When solar radiation intensity increases, the adsorbent maximum desorbing temperature increases too. There is an optimum desorbing temperature value too. When the desorbing temperature is greater than the optimum desorbing temperature the ratio of desorbed refrigerant mass will became weaker. This means that most of solar radiation intensity is used for metallic sensible heat; this will cause the COP of solar cooler decrease. The minimum value of solar intensity depends on the variations of the atmospheric temperature during the day and characteristics of solar cooler device, this minimum value is about 11 MJ/ m2 according to Ref. [25].

Effects of the Condensing Temperature

The performance of solar refrigerator is affected obviously by condensing temperature. In order to keep condensing temperature in a lower level, it is an effective way that adopting water to cool condenser instead of natural convection cooling. With the water cooling method, solar refrigerator can be worked in a suitable environmental condition, and the performance of solar system can be improved efficiently.

Effects of the Evaporating Temperature

The use of refrigerant other than water makes it possible that evaporating temperature is below 0°C.

From the previous discussion, significant improvements in the solar refrigerator performance can be obtained through a careful choice of a number of collector parameters. Generally speaking, enhancing the heat transfer between metallic plate and adsorbent, increasing the thermal conductivity of adsorbent are two obvious methods for improving performance of solar refrigerator. Increasing packing density of adsorbent, adopting double glass covers, using selective coating material as well as using heat transfer fins, all these ways are beneficial to increase properties of solar refrigerator. Simultaneously, choosing a suitable environmental condition may improve the performance of solar refrigerator.

2.7 Solar Adsorption Cooling Technologies

In order to improve the performance and the efficiency of the solar adsorbing cooling cycle, different cycles have been studied in addition to the basic cycle, continuous heat recovery cycle, mass recovery cycle, thermal wave cycle, convective thermal wave cycle, multi stage and cascading cycle etc.

2.7.1 Heat recovery adsorption refrigeration cycle

The semi-continuous heat recovery cycle is usually operated with two adsorption beds. The adsorber to be cooled will transfer its heat to the adsorber to be heated, which includes sensible heat as well as heat of adsorption. This heat recovery process will lead to a higher system COP. Multi-beds could be also adopted to get more heat recovery and thereby to attain higher COP, but the operation of a practical system will be complicated.

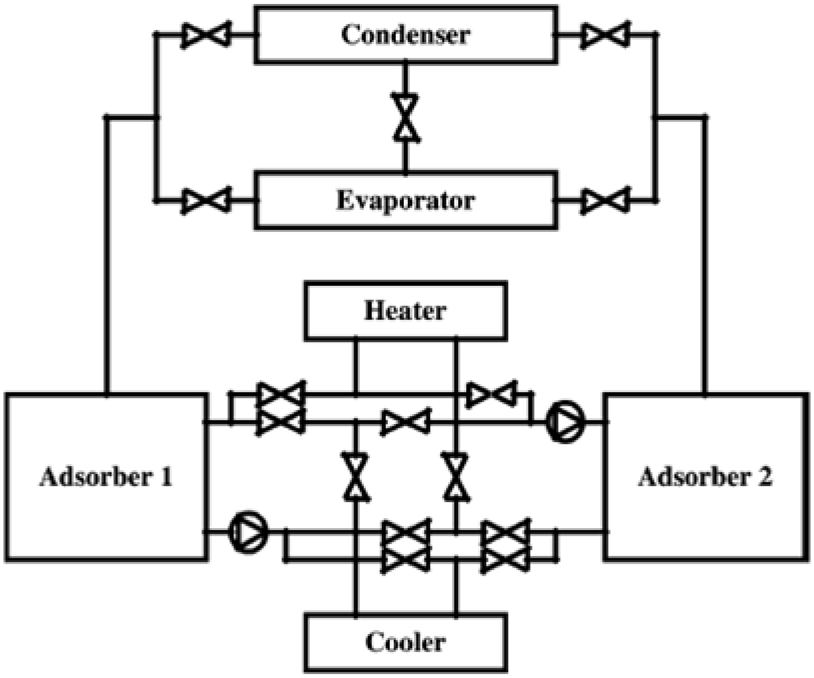


Figure 2.3: Schematics of heat recovery two-beds adsorption refrigeration system.

A quasi-continuous adsorption refrigeration system with heat recovery was investigated by Wang et al. [27, 28] and the flow path is shown in Fig.2.3. While adsorber 1 is cooled and connected to the evaporator to realize adsorption refrigeration in evaporator, the adsorber 2 connected to the condenser is heated to obtain heating-desorption-condensation. The condensed refrigerant liquid flows into evaporator via a flow control valve. The operation phase can be changed, and the go-between will be a short time heat recovery process. Two pumps are used to drive the thermal fluid in the circuit between two adsorbers (the connection to the heater and cooler are blocked during this process).

2.7.2 Mass recovery adsorption refrigeration cycle

Apart from the above discussed heat recovery operation, it had been proved that mass recovery is also very effective for heat recovery adsorption heat pump operation. In this process, at the end of each half cycle, one adsorber is cold and the other one is hot. Meanwhile, the former one which is at low pressure (PC) must be pressurized up to the condenser pressure, and similarly, the other one which is at high pressure must be depressurized down to the evaporator pressure. With just one tube between the adsorbers and a vapor valve, part of this pressurization – depressurization can be achieved by transferring vapor from the latter adsorber to the former one. This process can also be called as an 'internal vapor recovery process', and is reported to enhance the cooling power of the unit without reducing the COP by more than 10%. The above explained process involves only mass transfer and hence the process is rapid. To obtain a 'double effect', mass recovery could be initiated followed by heat recovery. An ideal heat and mass recovery cycle is shown in Fig 2.4, in which the heat recovery state for a two bed system is shown by the state points e –e'.

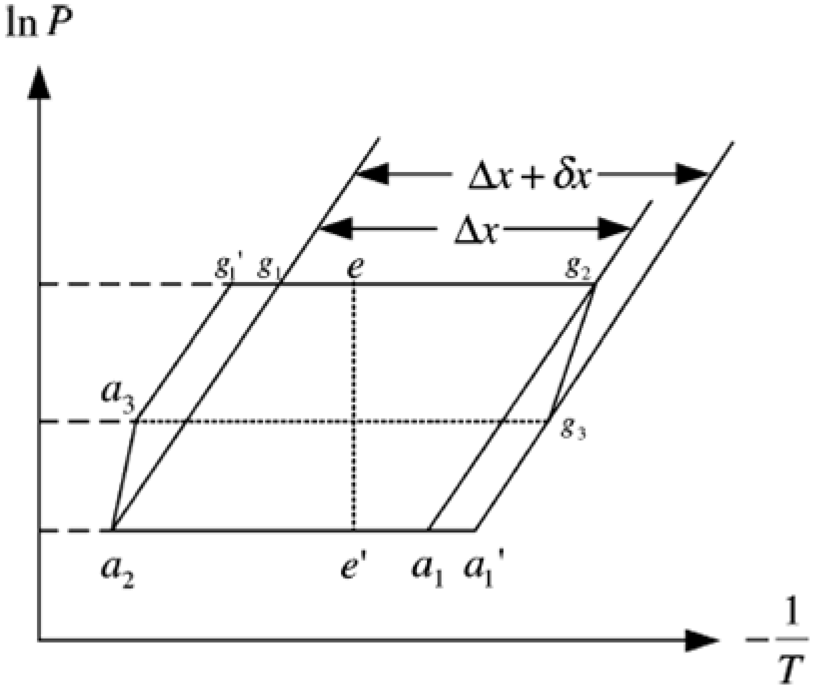


Figure 2.4: Diagram of heat and mass recovery cycle.

The mass recovery cycle(a2- a3- g'1- g2- g3- a'1- a1- a2) is an extended form of a two bed basic cycle or two bed heat recovery cycle(a2 - g1 -g2 - a1 -a2), and the cycled mass is increased from Δx to $\Delta x + \delta x$, which causes the refrigeration effect to increase. The principle of these cycles can be described using Fig.[29]. The very first part of each half cycle is the mass recovery process (path g2 - g3 and a2 -a3). Then the heat recovery process proceeds: heat is transferred from the hot adsorber to the cold one (path g3 – e'). As a consequence, the hot adsorber is first depressurized (path g3 – a'1), it then adsorbs vapor from the evaporator (path a' – e'). Meanwhile, the cold adsorber is first pressurized (path a3 –g'1), and then vapor that is desorbed passes into the condenser (path g'1 - e). Theoretically, the heat recovery process develops until the adsorbers reach the same temperature. Actually, there still remains a temperature difference between the adsorbers at the end of this period. Then, for closing each half cycle, the adsorbers are, respectively, connected to the heat source and heat sink (path e - g2 and e' - a2). The second half-cycle is performed the same way except that the adsorbers now exchange their roles. Due to this process, about 35% of the total energy transmitted to each adsorber can be internally recovered, including part of the latent heat of sorption.

2.7.3 Thermal wave cycle

To further improve the heat regenerative ratio, Shelton [30] had proposed an attractive cycle called 'thermal wave cycle'. In this process, it is assumed that a large temperature gradient exists along an adsorption bed. Heating and cooling of the adsorbent beds is achieved via a heat transfer fluid such as high temperature oil. The system consists of two adsorber beds and two heat exchangers connected in series to effect semicontinuous process. The function of the bed and heat exchanger is to combine a large area of heat transfer surface with a low oil flow rate.

A typical thermal wave cycle is shown in Fig 2.5. The cycle consists of two phases: In the first phase, the oil recovers heat from bed 2 (hot), has a further heat addition from the heat exchanger and then proceeds to heat bed 1 (cold). As the heating of the bed proceeds, bed 1 desorbs refrigerant which passes to the condenser (giving a useful heat output in the case of a heat pump) and bed 2 adsorbs gas from the evaporator which provides cooling. In the following phase (second phase) of the cycle the pump is reversed, and hence, bed 1 is cooled (adsorbing) and bed 2 is heated (desorbing) in a similar fashion until the original conditions are reached and the pump can again be reversed. Though the procedure is simple, significant heat recovery can be achieved. Further, the system would achieve much better performance due to the combination of the special nature of the internal bed heat exchangers and the low flow rate.

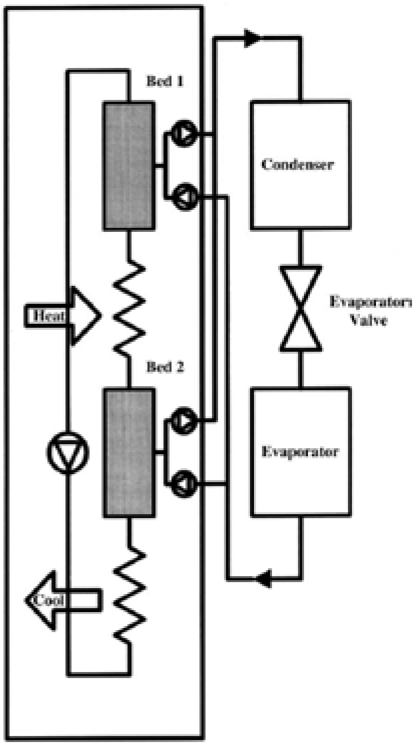


Figure 2.5: Thermal wave cycle.

Although many researchers have studied the cycle, up to now, there is no report of a successful prototype adopting thermal wave cycle. Also, some experimental reports had shown that the performance of the thermal wave cycle is not very good. The efficiency of the thermal wave regenerative system depends on a relatively large number of parameters: for example, rates of various heat transfer processes, the flow rate of the circulating fluid, the cycle time, the adsorber configuration, etc.

2.7.4 Convective thermal wave cycle

Thermal wave cycles normally suffer from low power density because of poor heat transfer through the adsorbent bed. Rather than attempting to heat the bed directly, it is possible to heat the refrigerant gas outside the bed and to circulate it through the bed in order to heat the sorbent. The high surface area of the grains leads to very effective heat transfer with only low levels of parasitic power needed for pumping. Hence, Critoph [31, 32] has presented a modified version of a thermal wave cycle, known as ‘convective thermal wave cycle’. The concept is the same as thermal wave cycle, however, the thermal fluid for heating and cooling to the beds is initiated by the refrigerant itself, thus the heat transfer between thermal fluid and adsorption bed is a direct contact heat transfer, which is incorporated with mass transfer in the system.

A practical schematic of the proposed system is shown in Fig.2.6. The two ‘active’ beds are packed with activatedcarbon and the two ‘inert’ beds are packed with non-reactive particles such as steel balls. The diagram shows the first half of the cycle, during which Active bed 1 is heated and desorbs ammonia while Active bed 2 is cooled, adsorbing ammonia.

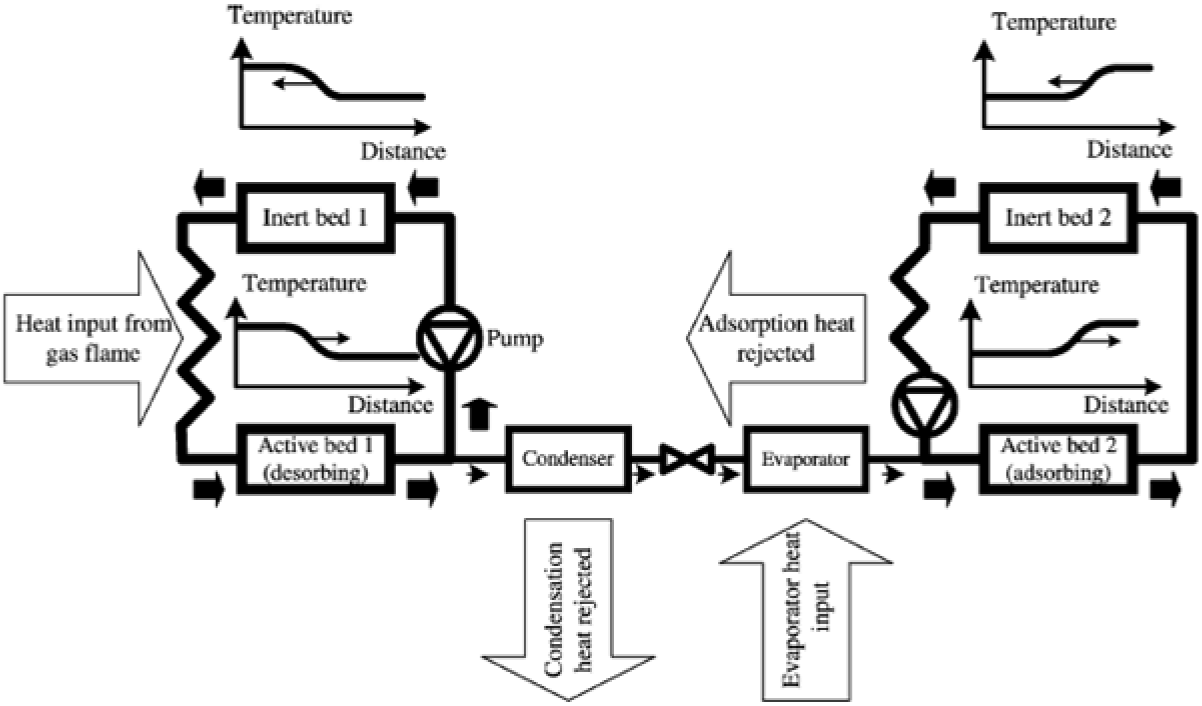


Figure 2.6: Convective thermal wave cycle

In the fluid circulation loop shown on the left, a low power pump circulates ammonia steam through inert bed 1 which is initially hot. The gas stream is heated by the bed and a 'cold' wave passes through the bed from right to left. Having been preheated by the inert bed, the ammonia stream is heated to the maximum cycle temperature (150–200 °C) in a heat exchanger. The ammonia gas then passes to active bed 1 where it heats the carbon. A 'hot' thermal wave passes from left to right through the active bed. As the temperature of the active bed rises it desorbs ammonia which first increases the pressure in the left hand loop and then condenses in the condenser, rejecting heat to the environment. The mass flow rate of circulating ammonia is typically ten times that of the condensing stream of ammonia and it may take about ten minutes for the two thermal waves to travel the length of their respective beds. In similar fashion to the left hand loop the circulating flow might be ten times the adsorption flow from the evaporator.

The advantages of this system are:

- The four packed beds are in effect heat exchangers of very high surface areas but at minimal cost. They are not only cheap but very compact.
- There are only four conventional heat exchangers and this is the minimum number allowed by thermodynamics. These are the evaporator and condenser, a gas heater whereby high-grade heat is input and a gas cooler whereby the low grade heat of adsorption is rejected to the environment.
- The cycle is highly regenerative since the packed beds act like large counterflow heat exchangers. This results in good energy efficiency (i.e. high COP).

2.7.5 Multi-stage and cascading cycle

The adsorption cycles discussed in previous sections are applicable only to a single stage cycle. The single stage cycle systems have certain limitations, that is, they cannot effectively utilize high temperature heat source, as well as do not perform well at very low temperatures. Hence, to improve the system performance under such situations, adsorptive processes may be adapted for advanced cycles, such as, multi-stage and cascading cycle.

The basic idea of a multi-stage cycle is to perform the desorption–condensation processes and evaporation– adsorption processes at different temperature/pressure levels by using the 'same working pair'. The internal re-use of heat of condensation or adsorption can increase the system performance significantly. Another practical cycle that can make good use of high temperature heat source is the 'cascading cycle', which operates with 'different working pairs' (either liquid/liquid or solid/liquid), such as zeolite– water/activated carbon–methanol, or zeolite–water/silica gel–water, etc. These cascading cycles are applied to situations especially, when there exists a large temperature difference between the heat source/ambient and the temperature in the evaporator/refrigeration space. For such situations, it may not be practical to use single stage cycle. Hence, one way of dealing with such situations is to perform the evaporation/refrigeration process in stages, that is, to have two or more cycles that operate in series at different temperature levels (cascading). A high temperature heat source (e.g. boiler) is used to drive the high temperature stage adsorption refrigeration cycle. The low temperature stage adsorption refrigeration is driven by sensible heat and heat of adsorption obtained from high temperature stage.

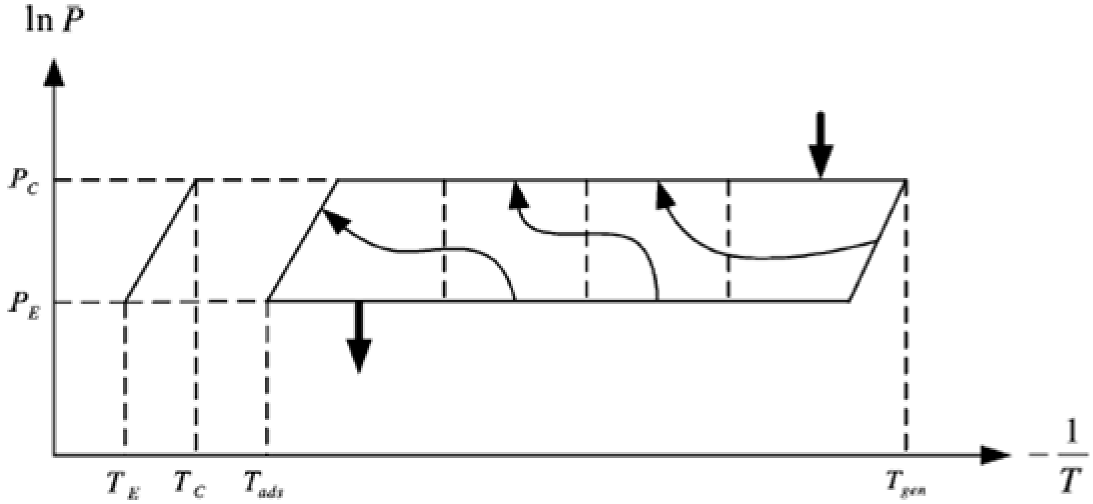


Figure 2.7: n-Adsorber cascading cycle.

To minimize the contribution of sensible heat, special care has been attached to the heat management of the adsorbers; n-adsorber cycles operating with a single evaporator and a single condenser have been proposed with sequences of heat recovery between adsorbers. Such cycles offer some advantages: for example, a single condenser is used and pressure in the n-adsorber unit is not higher than that in the unit operating an intermittent cycle; moreover, adsorption heat at high temperature is used as desorption heat at low temperature. Counteracting heat transfer fluid circuits between adsorbers reduces entropy generation in comparison with what happens in intermittent cycles. The driving heat supplied to the cycle is at high temperature level (Fig.2.7)[29]so that the entropy generation—due to the inadaptation between the temperature levels of the source and of the adsorber is much less in an n-adsorber cycle than in an intermittent cycle. The same thing happens for the rejected heat: the rejection temperature is much closer from the utility temperature with an n-adsorber cycle than with an intermittent cycle.

Chapter 3

Potential of Solar Energy in India

3.1 Solar Energy

The basic resource for all solar energy systems is the sun. Knowledge of the quantity and quality of solar energy available at a specific location is of prime importance for the design of any solar energy system. Although the solar radiation (insolation) is relatively constant outside the earth's atmosphere, local climate influences can cause wide variations in available insolation on the earth's surface from site to site. In addition, the relative motion of the sun with respect to the earth will allow surfaces with different orientations to intercept different amounts of solar energy.

In India also we have very good potential of solar radiation and it could be used for many purposes, however, solar energy is available over the entire globe, and only the size of the solar system needs to be increased to provide the same amount of heat or electricity as in the shaded areas. It is the primary task of the solar energy system designer to determine the amount, quality and timing of the solar energy available at the site selected for installing a solar energy conversion system.

Just outside the earth's atmosphere, the sun's energy is continuously available at the rate of 1,367 Watts on every square meter facing the sun. Due to the earth's rotation, asymmetric orbit about the sun, and the contents of its atmosphere, a large fraction of this energy does not reach the ground. The effects of the atmospheric processes that modify the incoming solar energy, how it is measured, and techniques used by designers to predict the amount of solar energy available at a particular location, both instantaneously and over a long term must be discussed.[33]

3.1.1 Solar Radiation Components

Through the atmosphere the solar irradiance decreases and the spectral distribution changes. Ozone absorbs the ultraviolet radiation while water vapor, carbon dioxide and other greenhouse gases absorbs some of the infrared radiation. In the visible spectrum, the shortest wavelengths (i.e. the blue light) is scattered by air molecules and dust. Therefore only part of this radiation reaches the surface, and in the form of diffuse radiation (figure 3.1).[34] The sum of the diffuse and direct radiation (that travels uninterrupted through the atmosphere, often called beam radiation) is referred to as the global irradiance. The direct normal irradiance is the radiation at a surface normal to the direct radiation. This component is used to define the angle of incidence, θ, as the angle between the direct normal radiation and the normal to the surface of interest. The irradiance on a surface varies with the cosine of the incident angle: $Eg = Ed + Er + En * \cos\theta$, Where, Ed is the diffuse irrdiance, Er is the ground reflected irradiance and En is the direct normal.

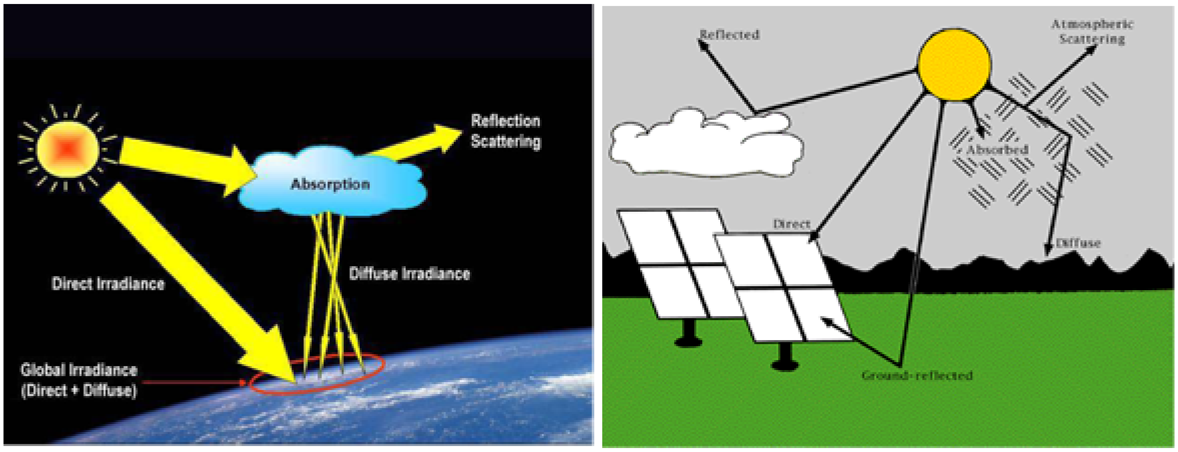


Figure 3.1: Sketches of the solar radiation

3.1.2 Measurement of Solar Radiation – Pyranometer

A pyranometer is an instrument used to measure the global radiation (figure 3.2). The instrument has a hemispherical view of the surroundings. By adding a shading ring, the direct radiation is excluded by which the pyranometer measures only the diffuse radiation. A pyranometer uses thermal sensors. One sensor is exposed to the solar radiation, while the other is shaded. The temperature difference registered by the sensors is used as a measurement of the solar radiation..

Figure 3.2: Pyranometer

3.2 Climate and Potential of Solar Radiation in India

3.2.1 Climate in India

As the characteristics of the cooling demand are different at various locations, depends on solar radiation , temperature level and other climate conditions therefore we need to analyze our local country climate.

India, being a vast country does not fit into any one zone. Situated roughly between 8° N and 37° N Latitude, it occupies a large area of South Asia. It can be divided mainly into four climatic zones namely Alpine, Subtropical, Tropical and Arid.

Alpine Zone: This climate zone can be experienced in the high altitudes of Himalayas. In this region there are high climatic fluctuations due to steep altitude variations. Different types of climatic zones can be seen in this region. If on the foothills occur subtropical climate there is Alpine Tundra Zone to greet you on the higher altitudes.

Sub Tropical: This zone is prevalent in most of the northern part of India. It can be called as the typical Indian climate. Summers are hot and wet while in winter temperature may drop down to freezing point in higher ranges. Rainfall is common in monoon season whereas winters are cold and dry.

Tropical: It can be divided into two sub types viz, Tropical Wet Monsoon and Tropical Dry. The characteristics of Tropical Wet Monsoon include average temperature, which normally does not fall below 18 $^\circ C$, accompanied by average to high rainfall. In Tropical Dry type rainfall is not so common.

Arid: High temperature and low rainfall are marked features of this climatic zone. It is prevalent in western part of the country and includes large part of Rajasthan. The temperature in this zone may shoot up to as high as 50 $^\circ C$ in summer.

Cycle of Season

Though divided into different climatic zones, India seems to be unified by primarily four seasons- Winter, Summer, Advancing Monsoon and Retreating Monsoon.

Winter: December to February is the wintertime in almost all of India. At this time of the year, days are cold with average temperature of 10-15 $^\circ C$, but it can drop down to below 0 $^\circ C$ in some higher ranges of northern India. Normally winters are dry in northern India. In Southern part, the temperature difference is not so marked due to moderating effect of Indian Ocean, Bay of Bengal and Arabian sea.

Summer: March, April, May and June are the summer months in India. It is a time period when rays of the sun fall vertically on Indian subcontinent. The average temperature is around 32 $°C$ but in western region the maximum temperature can be far above the average.Hot wind, known as ‘Loo’ is the marked feature of summers in India.

Advancing Monsoon: It is the time period when India gets major part of its share of rain. Months of June, July, August and September form the core of Advancing Monsoon in almost all parts of country. The monsoon approaches with moisture laden winds, this sudden approach is marked with violent thunderstorms and lightening, known as ’break’ of the monsoon.

Retreating Monsoon: This season starts, when monsoon after drenching all of India, begins to retreat. With the month of September, rainfall began to decrease and as we approach November, the monsoon is completely gone from major part of India, except for Tamil Nadu and some other southern states, which also receive rain from Western Disturbance. [35]

3.2.2 Potential of Solar Energy in India

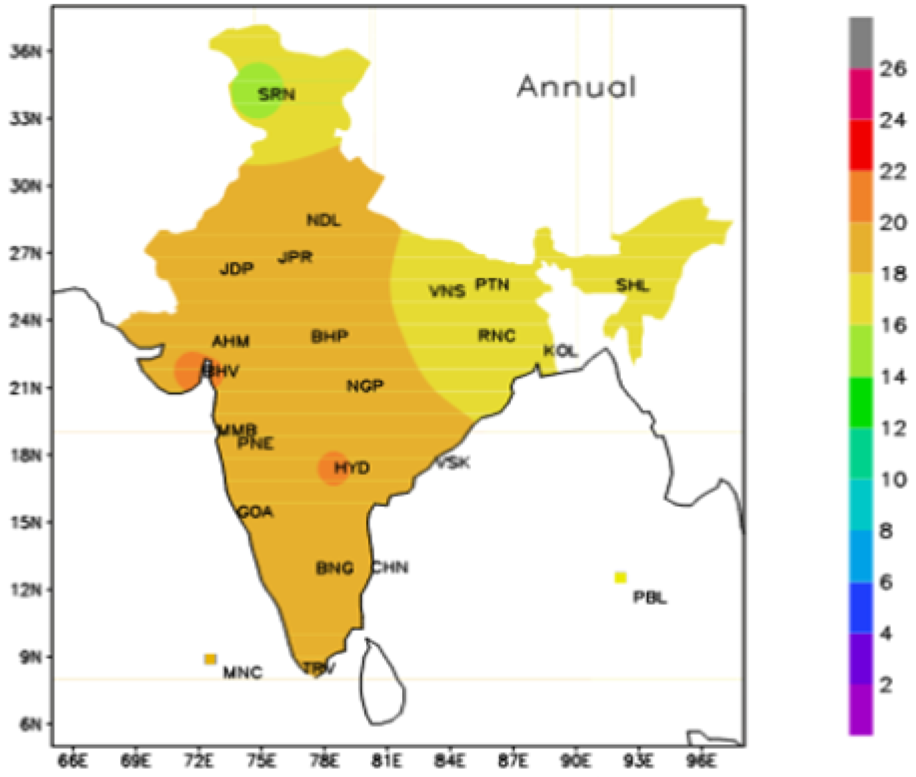


Figure 3.3: Global solar radiant exposure over the year – MJ/m^2

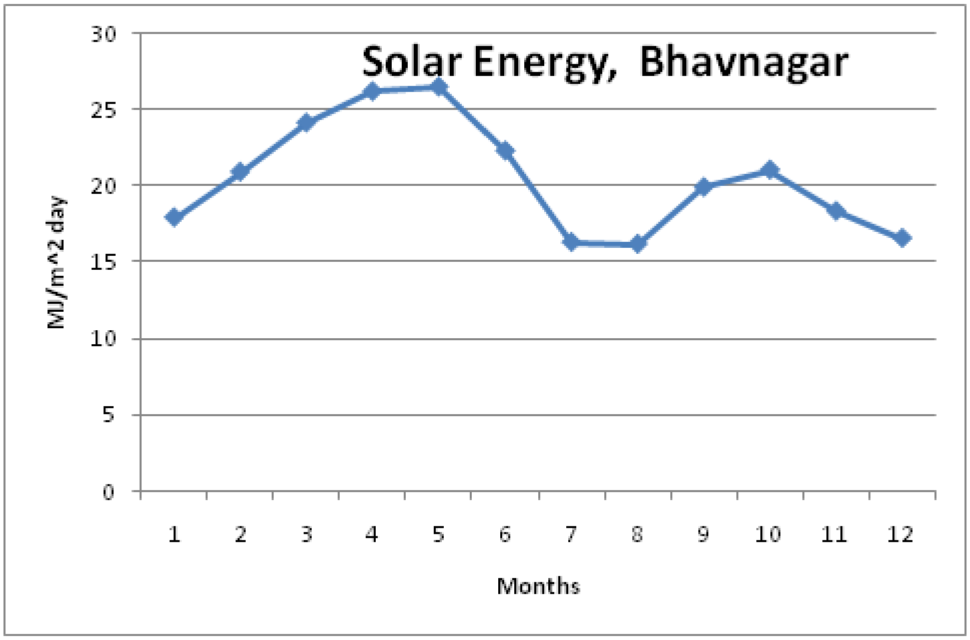


Figure 3.4: The average total solar radiation per day for each month

These figures3.3and 3.4 [36]are encouraging to exploit the solar energy for different applications such as water heating, drying of crops, vegetables and fruits, water desalination, water pumping and electrification of remote locations isolated from the electrical networks, and we hope for cooling.

Chapter 4

Design and Fabrication of Component

In the experiments, adsorption refrigeration system is considered to have three main components which are adsorber or collector, condenser and evaporator respectively. We have designed evaporator for freezing 2 kg of water and designed the condenser and collector too.

4.1 Adsorber or Collector

Material Selection :- Recent research showed that the aluminum alloy have a stronger catalytic effect on the decomposition reaction under the solar adsorption refrigeration, therefore mild steel is used as adsorbent heat transfer metal instead of aluminum alloy although mild steel has poor heat transfer ability than that of aluminum alloy.[37] In terms of cost effectiveness also mild steel is suitable. Mild steel contains 0.16-0.29% carbon, therefore it is neither brittle nor ductile. It has a relatively low tensile strength, and its surface hardness can be increased through carburizing. Density of M.S is 7.85 g/cm^3. Thermal conductivity is 40 to 60 W/mK.

Design

If water is available at 25 °C and then to achieve -5 °C temperature amount of heat extracted from water is

$Q = M_w * C_{pw} * \Delta T_w + M_w * H_{lf} + M_{ice} * C_{pice} * \Delta T_{ice}$

Where,

M_w = mass of water = 2 Kg

C_{pw} = specific heat of water = 4.187 KJ/KgK

$\Delta T_w = T_{h1} - T_{h2}$, $T_{h1} = 25\ °C$, $T_{h2} = 0\ °C$

H_{lf} = latent heat of fusion of ice = 333.3 KJ/KgK

M_{ice} = mass of ice = 2 Kg

C_{pice} = specific heat of ice = 2.093 KJ/KgK

$\Delta T_{ice} = T_{h2} - T_{h3}$, $T_{h3} = -5\ °C$

Q = 913.17 KJ

Solar adsorption refrigeration system to produce 2 kg of ice during 12 hours (8 pm to 8 am) i.e during off Sun shine hours which is a favorable period for the adsorption system. For this required to calculate cooling capacity

Capacity of cooling = 913.17/12*3600 = 21 W

Considering 20% losses

Capacity of cooling = 21/0.8 = 27 W

Now, considering 50% desorption rate, and latent heat of methanol at -10 °C is 1182 KJ/Kg.

So, we can found out methanol required

= (913.2)/(0.8*0.5*1182)= 2 Kg

Methanol Required = 2 Kg

Adsorption capacity of activated carbon(granules) was taken as 0.284 Kg of Methanol/Kg of AC.[37]

Activated carbon of size1.5 mm was used.

Hence required quantity of carbon = 2/0.284= 7 Kg

Area required for adsorbent bed is calculated by

Density= mass / volume

300 = 7/volume

Volume = $0.023 m^3$

Taking depth of 0.03m, Area = 0.023/0.03 = 0.76 m^2

We taken 0.90 m^2 of area because the copper pipe of 12.5 mm diameter and 80mm length (9 nos.) is placed into the adsorbent bed.

- In the top plate fins are provided to increase the heat transfer inside the adsorbent bed.

- Average 18MJ/m^2 to 27 MJ/m^2 per day solar energy is falling on the horizontal surface.

- We placed adsorbent bed on an inclination of 15 degree, so we calculated the solar radiation falling on inclined surface.

Calculation of solar intensity on an inclined surface [39]

19 MJ/m^2 energy falling on the horizontal surface on date 15.3.11.

The intensity on an inclined surface was calculated using the following equations :

$\cos\theta_z = (\cos\phi + \cos\omega) + (\sin\delta + \sin\phi)$

Where ϕ is the latitude, δ is the declination or angular position of sun at solar noon; ω is the Hour angle which is the angular displacement of sun east or west of local meridian due to rotation of earth on its axis at 15° per hour, morning before 12:00 noon is negative, afternoon is positive; θ_z is the zenith angle which is the angle of incidence of beam radiation on horizontal surface.

Declination $\delta = 23.45*\sin((360*(284+n)/365))$

Assuming it is a tropical climate the following correction factors are used:

$r_o = 0.95$, r_1= 0.98, $k_1 = 1.02$

Thus

$a_o = r_o(0.4237 - (0.00821(6 - A)^2))$

$a_1 = r_1(0.5055 + (0.00595(6.5 - A)^2))$

$k = k_1(0.2711 + (0.01858(2.5 - A)^2))$

$\tau_b = a_o + (a_1 \exp(-k/cos\theta_z))$

$\tau_d = 0.271 - (0.2939\tau_b)$

Where τ_b and τ_d are the transmittances of the atmosphere for beam and diffused radiations. a_o, a_1 and k are constants for standard atmosphere with 23 km visibility.

$I_{clear} = I_{sc}cos\theta_z(1 + (0.033\cos(360n/365)))(\tau_b + \tau_d)$

$I_d/I_h = 1 - 0.1I_h/I_{clear}$

$I_b = I_h - I_d$

$R_b = (cos(\phi - \theta)cos\delta cos\omega) + (sin\delta sin(\phi - \theta))/((cos\phi cos\delta cos\omega) + (sin\phi sin\delta))$

$I_t = I_bR_b + I_d(1 + (cos\theta)/2) + I_h\rho_r(1 - (cos\theta)/2)$

$I_c = I_t*$Reflection correction factors

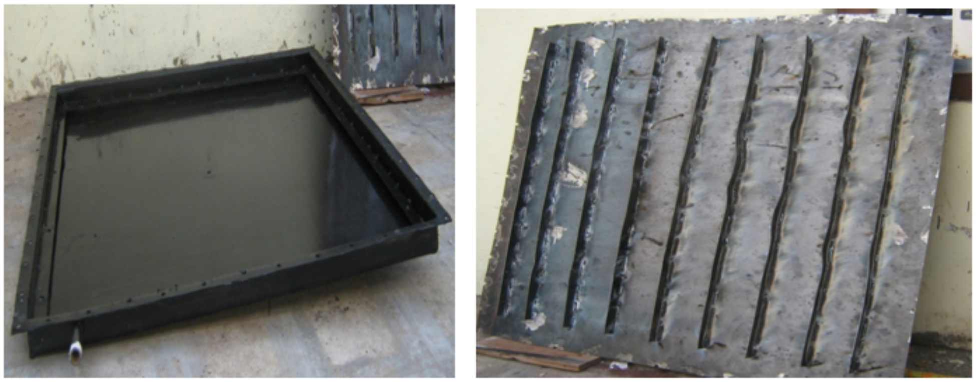
Where θ is the collector tilt, n is the average day of month taken from table 1.6.1 [39]; I_{clear} is the clear sky radiation, I_d is the diffused radiation, I_b is the beam radiation, R_b is the ratio of beam radiation on tilted surface to that of horizontal surface, I_{sc} is the solar constant $=$ 1353 W/m^2, I_h is the intensity on a horizontal surface, I_t is the total intensity on inclined surface without reflectors and ρ_r is the reflectance of the glass cover.

Calculation presented in the Appendix A

By putting all appropriate values in above equations we get total energy on inclined surface as 22MJ$/m^2$.

Fabrication

- Basic Size of M.S sheet is 8 ft * 4 ft, thickness 2.33 mm
- From sheet we cut one top plate of size 0.95 m^2 and another bottom plate of size 1 m^2 by using press machine.
- With top plate fins of size (85 mm* 27 mm *1.8 mm) is attached by using arc welding technique. No of fins is 9 as shown in fig 4.1
- A galvanized iron sheet with number of holes is placed in the bottom plate (above 1.5 cm upward from bottom) to support the metallic mesh as shown in figure 4.2
- The metallic mesh is placed on the galvanized sheet so that carbon particles are held in place as shown in figure 4.2.
- On metallic mess 7 Kg of carbon is placed.
- Inside the bed copper pipes are placed with four holes on the circumference at distance of 5 mm so methanol can easily flow through them. All pipes are connected with common header through soldering. 4.3
- On the copper pipes a metallic net is provided to prevent carbon particles from entering in the pipes.4.3
- After placing activated carbon on the metallic mesh top plate is welded through Arc Welding.
- Then pressure testing is carried out to found out leakage in the adsorber.
- Then again welding is done where leakage is found out.
- Now, adsorber is ready as shown in fig.4.4



(a) (b)

Figure 4.1: (a) Photo of bottom plate (b) Photo of top plate with fin

(c) (d)

Figure 4.2: (c) Galvanized iron sheet with number of holes (d) Metallic mesh

(e) (f)

Figure 4.3: (e) Copper pipes connected with common header (f) Net provided on the pipes

Figure 4.4: Adsorber or Collector

4.2 Condenser

Material Selection :- To condense the vapor effectively it is required that good heat transfer occur between condenser tubes and water. We have chosen copper tubes to construct the condenser because of high thermal conductivity.

Design[38] :-

Condenser is also considered as surface type heat exchanger where desorbed methanol from collector gets condensed. Here two types of condenser are used:-

Condenser 1

Step :- 1 find out T_{c2} from the heat balance equation

Q = Mw*Cpw*(Tc2-Tc1)=Mm*Hfg

$Q = M_w * C_{pw}(T_{c2} - T_{c1}) = M_m * H_{fg}$

Where,

Q = Heat flow rate in W

M_w= Mass of water = 40 Kg

C_{pw}= Specific heat of water = 4.187 KJ/Kg K

T_{c1} = Intial temperature of water = 20 $°C$

T_{c2}= Final temperature of water in $°C$

M_m= Mass of methanol = 2 Kg

H_{fg}= Enthalpy of liquid gas phase of methanol = 1100 KJ/Kg

by substituting above value we get

T_{c2}= 33 $°C$

Step :- 2 Now find out ΔT_m

$T_{h1} = T_{h2}$ for condensation process =64.5 $°C$

$\theta_1 = T_{h1} - T_{c1}$, $\theta_2 = T_{h2} - T_{c2}$

ΔT_m= logarathmic mean temperature difference

$\Delta T_m = (\theta_1 - \theta_2)/\ln(\theta_1/\theta_2)$

ΔT_m= 37

Step :- 3 Find out size of heat exchanger (condenser)

$Q = A_o * U_o * \Delta T_m$

Where,

U_o= Overall heat transfer coefficient in W/m^2K = 1022 [38]

A_o= Total heat exchange area in m^2

$Q = M_m * H_{fg}$= 2200 KJ/Kg

by substituting above values we get,

A_o= 0.05732 m^2

Step :- 4 calculate length of tube

$A_o = \pi * d_o * l * N_t$

Where,

d_o= Tube outer diameter = 0.0125 m

l = length of tube in metre

N_t= Number of tubes = 1

by substituting above value we get,

l= 1.46 m

Fabrication

- By using bender, we made a helical coil of 1.47 m length.

Figure 4.5: Water cooled condenser

Condenser 2

We have condenser with 2 headers of (l_1= 0.60 m) length and (d_1 =0.016mm) diameter as well as 11 number of tubes of (l_2 = 0.30m) length and (d_2 = 0.0095m) diameter along with 77 fins of 0.05m *0.15m respectively.

$$\text{Surface area} = (2 * \pi * r_1 * l_1 * N_H) + (2 * \pi * r_2 * l_2 * N_T)$$

$$= 0.1587\ m^2$$

Available bare suraface area is 0.1587 m^2.

Figure 4.6: Water cooled condenser2

4.3 Evaporator

Material Selection :- The various materials are available among them we choose copper because it has high thermal conductivity around 300 W/m^2k and easy to fabricate. We have chosen 1.5 mm thick copper sheet because it is required that plate have sufficient thickness so it can withstand the vacuum as well as positive pressure during operation of the system.

Design

Evaporator is the component where the ice formation takes place. The evaporator must have sufficient volume to collect the entire condensed methanol. In order to enhance the heat transfer effect, the heat exchange surface is designed as a series of four trapezoidal cells shown in Fig. Here fluid inside evaporator is methanol and surrounding fluid is water.

Heat transferred from water to methanol is addition of sensible heat transfer for water temp. gradient of 25 $°C$, and latent heat transfer for freezing of w

$$Q = M_w * C_{pw} * \Delta T_w + M_w * H_{lf} + M_{ice} * C_{pice} * \Delta T_{ice} \tag{4.1}$$

Where,

M_w = mass of water = 2Kg

C_{pw} = specific heat of water = 4.187 KJ/KgK

$\Delta T_w = T_{h1} - T_{h2}$, $T_{h1} = 25\ °C$, $T_{h2} = 0\ °C$

H_{lf} = latent heat of fusion of ice = 333.3 KJ/KgK

M_{ice} = mass of ice = 2 Kg

C_{pcice} =specific heat of ice = 2.093 KJ/KgK

$\Delta T_{ice} = T_{h2} - T_{h3}$, $T_{h3} = -5\ °C$

By substituting values in equation (4.1) we get,

Q = 913.17 KJ

This much amount of heat is taken by methanol for vaporization.

Assuming methanol evaporation temp. around -10 $°C$ and latent heat at -10 $°C$ to be 1182 KJ/Kg. We have designed an evaporator which hold 2 Kg of methanol and calculated maximum surface area of 0.1696 m^2.

The evaporator is immersed in a water tank, which is made of poly methyl methacrylate(PMMA) sheet, and both the evaporator and water tank are placed in Thermocol

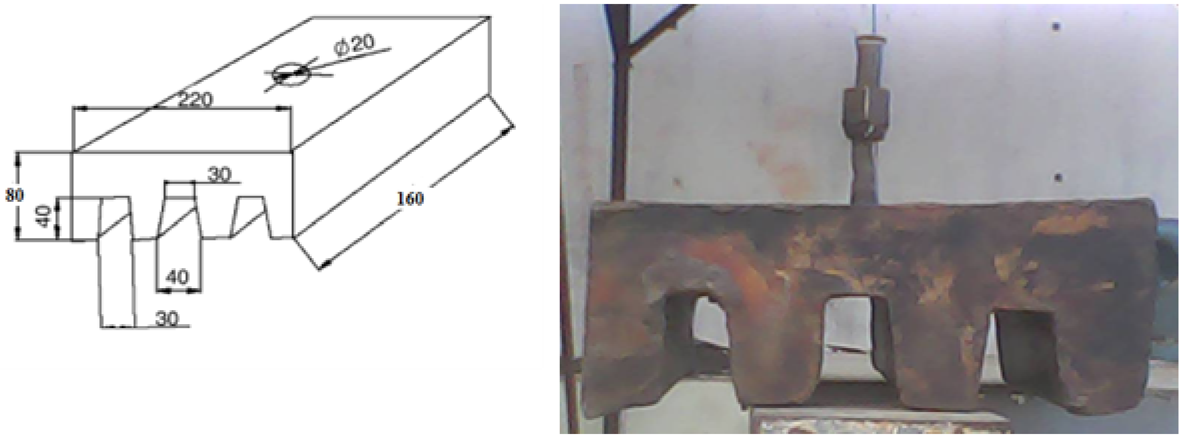


Figure 4.7: Evaporator drawing

box which itself act as a insulation materialas shown in figure 4.8. In this way, it is very simple to remove the ice if be formed during adsorption cooling in the night.

Figure 4.8: Evaporator Box

Reservoir

Material Selection :- We have made a two types of reservoir with capacity of 2 Kg. The size of reservoir is 0.20*0.10*0.10 m.

Reservoir 1

The material used for this is galvanized sheet of 1.5mm thickness and plain glass of thickness 5mm on which marking is provided. By using reservoir we can measure the quantity of methanol desorbed from the adsorbent bed. The problem lies with this reservoir is it cannot be made leak proof.

Reservoir 2

The material used for this is PMMA(poly methyl methacrylate) sheet of 12mm thickness. The marking is provided on the sides to see the quantity of methanol desorbed. It can be made completely leak proof. The main problem with this reservoir is in long run it reacts with methanol.


(a)

(b)

Figure 4.9: (a) Reservoir 1 (b) Reservoir 2

Pipes

Material Selection(Pipes) :- To connect whole system copper pipes of 12.5 mm(1/2 inch) diameter is used. As copper pipes are easy to bend with bender tool.

Chapter 5

Experimental Work, Results and Discussion

5.1 Working Principle of Solar adsorption chiller

The working principle is described as follows: On a sunny day, the adsorbent bed absorbs solar radiation energy, which raises the temperature of adsorbent bed as well as the pressure of refrigerant. The desorbed refrigerant vapor condenses into liquid in the condenser and flows into the evaporator directly; this desorption process lasts until the temperature of adsorbent reaches the maximum desorption temperature. During night, when the temperature of the adsorbent bed decreases, the refrigerant vapor from the evaporator adsorb in the adsorbent bed.

During this adsorption process, the cooling effect is released from refrigerant evaporation, and the ice is expected to form in the water tank placed inside thermal insulated water box.

5.2 Construction of Solar Adsorption Chiller

5.2.1 Adsorbent Bed

Adsorbent bed is the most important part of the solar chiller, it is the heart of solid adsorption refrigeration, and the characteristics of the adsorbent bed are the most obvious factors which directly affect solid adsorption systems. For the flat-plate solar chiller, the collector and adsorbent bed are often designed into an integrated shape to enhance heat transfer.

At the same time, several fins are necessary to enhance heat transfer, so that the heat received by the adsorbent bed top surface can be quickly transferred inside the bed. Usually, this type of adsorbent bed possesses good heat transfer ability [40]. Generally speaking, a good adsorbent bed must have good heat and mass transfer.

For the experiments, The adsorbent bed is a flat plate mild steel box, having effective surface area of nearly 0.90 m2, in which about 7 kg adsorbent (activated carbon) is charged. The box is painted in matt black to enhance receiving solar flux radiation. Except for the top surface, every side of the adsorbent bed is covered with insulation material.

On the top of the adsorbent bed, a glass cover is placed to form a "greenhouse" effect. To increase heat flux reflectors are provided which are shown in fig 5.1. The size of reflector is 112 cm * 54 cm. However, in the evening, a moveable damper may be installed to effectively cool the adsorbent bed by air.

Figure 5.1: Collector with reflector

As mentioned previously, in order to guarantee better heat transfer between the front side and the adsorbent, fins (also made of mild steel) are placed inside the adsorbent bed box in contact with the front side and the activated carbon. The distance between these fins is approximately 10 cm. The thickness of the adsorbent layer is about 3 cm. The schematic diagram of adsorbent bed is shown in fig 5.2.

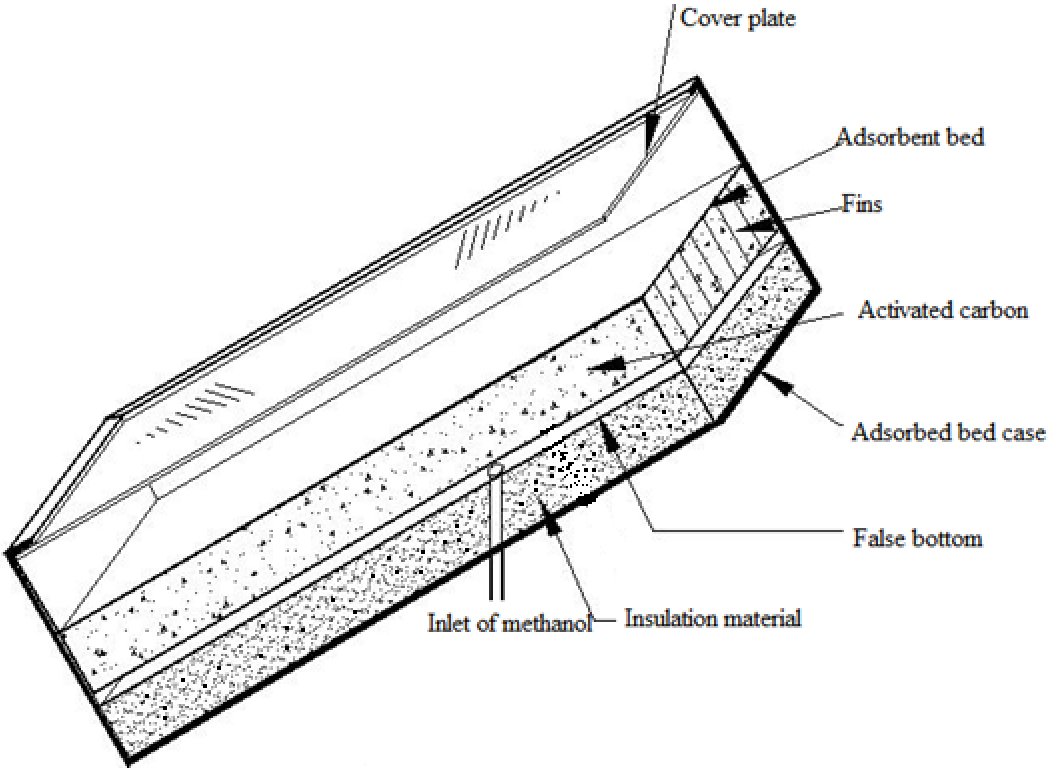


Figure 5.2: Schematic of collector

In order to improve the transfer of methanol vapor through the activated carbon layer, a false bottom (1 cm thick) is included in the rear side of the adsorbent bed as mentioned by [14]. As this “false bottom” is completely open to the circulation of vapors, it permits uniform distribution of methanol in the adsorbent.

5.2.2 Condenser and Evaporator

During the process of desorption of methanol, a well designed condenser is needed to reject the desorbed heat. Two different condenser are tested for this purpose, one was helical copper tube immersed in a water tank and another copper tube attached with fin type condenser. The evaporator must have sufficient volume to collect the entire condensed methanol. In order to enhance the heat transfer effect, the heat exchange surface is designed as a series of four trapezoidal cells. The material used for evaporator is copper sheet, thickness is 1.5 mm.The dimension of the evaporator is 220×160×80 mm and the heat exchange area is about 0.1696 m^2.

5.2.3 Integration of the Subsystem

The adsorber bed, condenser, evaporator were hermitically sealed and checked for vacuum proof. They are then connected with each other using copper pipe of 1/2 inch. A receiver made of poly methyl methacrylate (PMMA) was provided to collect desorbed methanol between condenser and evaporator. The whole system was mounted on a frame bracket installed with wheels, to make it a movable unit. A pressure gauge is installed on the adsorbent bed outlet pipe to check for the pressure conditions in the system. Between adsorbent bed outlet pipe and condenser inlet charging line was provided to charge the methanol in the adsorbent bed and also attaching a vacuum pump whenever needed. The schematic diagram of solar adsorption chiller is shown in fig 5.3.

Two thermocouple were used for monitoring the temperature one positioned on the absorber surface and the other in the water of the evaporator. The photograph of the system is shown in Fig.5.4. In order to ensure that the system can work normally, it is essential that the whole system should be hermitically sealed.

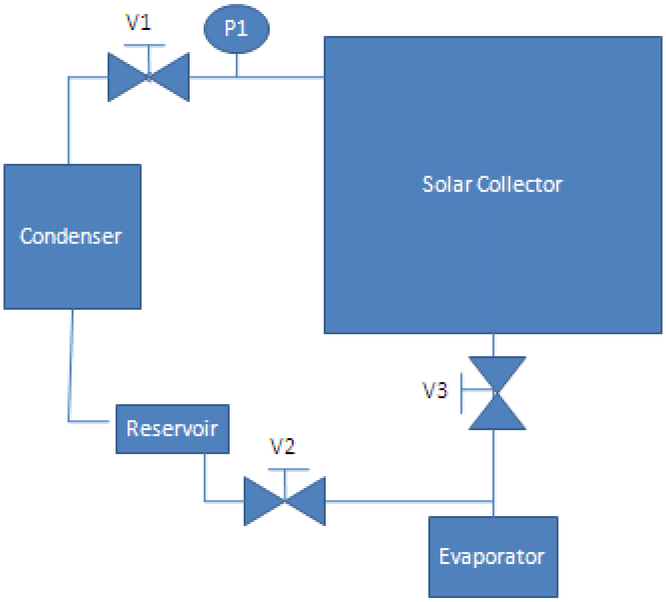


Figure 5.3: Schematic of Solar adsorption chiller

Figure 5.4: Photograph of solar adsorption chiller

5.3 The Experimental Method

The design, construction and test run of a solar adsorption Chiller are presented to see if a cooling process is achieved or not.

Experiments using two types of condensers were made as mentioned previously, the first by using a helical copper pipe immersed in a water tank, and the other by using an finned condenser immersed in a water tank.

After the construction of the system, several tests were performed to ensure good sealing, since any kind of air leakage inside the system is bound the lead to failure of the process. The total pressure may increase due to leaks or desorption of air from activated carbon, then the adsorption of methanol is reduced.

5.3.1 Commissioning of the set up

At start of the experiments , the system was evacuated at elevated temperature to flush out entrapped air/moisture using a vacuum pump until full vacuum was reached. This was also used to test the system for any leakage. Charging the adsorbent bed with methanol done in the night. During charging, all valves were closed except valve that controls the charging line. Since adsorption is an exothermic process,heat is liberated to the immediate environment . This heat is dissipate by natural convection and night sky radiation by opening the collector box end cover plates so that air flows over the collector plate. At the start of solar heating(around 8:00am), collector box end cover plates and all valves were closed. Valve V1 linking the collector tubes with the condenser also remained closed at this initial period of heating. As the solar heating progressed, the pressure in the system increased with the absorbed methanol mass remaining constant. This is the isosteric period. At the onset of methanol desorption , indicated by the value of pressure inside the collector tubes and at about 10:00a.m. local time, valve V1 opened. While other valves remained closed.The desorbed methanol flow through the condenser coil and collected into reservoir. The adsorbent bed top plate temperature, volume of condensate, ambient temperature and collector pressure were monitored and recorded during this period. Upto evening desorption and simultaneously condensation was allowed to occur. After that (at about 5:30pm) glass cover of the collector was opened and valve V2 was opened for some period to allow liquid methanol to collect inside the evaporator. At 8:00pm valve V3 was opened and valve V1 as well as V2 was closed so that adsorption could proceed through evaporator to collector via Valve V3. The above procedure repeated again for next few days.

5.4 Result Data

Experiment :-1

The first experiment was done on the 08th February 2011 , at 7:00 pm. The system was evacuated to 6 KPa, then the system was charged with 2 Kg of methanol, and the condenser tank was filled with 40 liters of water and the cooler box with 2 Kg of water.

Parameters such as the temperature of the adsorbent bed, top plate temperature, condenser water temperature, ambient temperature, water temperature inside the cooling box and the pressure were monitored and recorded. The temperatures were measured by thermocouples placed in the system.

The output data indicated as shown in Tables

Where:

T_1: Adsorbent bed top plate temperature.

T_2: Temperature of the water inside the cooler box.

T_3: Temperature of the condenser water.

Tamb: Ambient temperature.

Pcond : Pressure at the inlet of condenser.

The temperature and pressure data at various time was summarized in the table below .

Table 5.1: Results of charging the 2 Kg of methanol with starting pressure of 14 KPa

Date	Time	State	$T_1\ ^{\circ}C$	$T_2\ ^{\circ}C$	$T_3\ ^{\circ}C$	Tamb $^{\circ}C$	Pcond (KPa)	Remarks
9.2.11	8 :30am	Before Heating	25	20	18.5	20	14	There was no cooling obsreved
	14:00pm	Through Heating	117	25	22	33	143	
	18:00pm	End of Heating	33	25	22	26	61	
	19:00pm	Cooling	26.3	25.7	21.6	23	33	
10.2.11	8:00am	Adsorption	25	20	18.5	20	67	
	8:30am	Before Heating	25	20	19	21	67	
	14:00pm	Through Heating	117	25	22	34	137	
	18:00pm	End of Heating	33	25	22	28	61	
	23:00pm	Cooling	27.2	26	22	28	52	
11.2.11	8:00am	Adsoprtion	25	20	18.5	25	81	

Remarks:- Condensation presssure was going very high and due that insufficient condensation took place.

So, we decided to test condenser 2.

Experiment :-2

2 Kg of methanol is charged on date 14.3.11 at 10:00pm. The pressure in the system at that time is 24 kPa.The condenser 2 was used. The temperature and pressure data at various time was summarized below in the Table.

Table 5.2: Result of charging 2 Kg methanol with starting pressure of 41 kPa

Date	Time	State	T_1 °C	T_2 °C	T_3 °C	Tamb	Pcond (KPa)	Remarks
15.3.11	8 :30am	Before Heating	22.5	25.4	18	26	41	There was no cooling observed
	11:45am	Through Heating	106	28	22	33.1	118	
	02:00pm	Through Heating	126	30	23	37.8	108	
	17:00pm	End of Heating	49	32.2	22	43.1	71	
	19:00pm	Cooling	23	33	22	31	27	
16.3.11	8 :00am	Adsorption	19.3	20	19	23	41	
	8 :30am	Before Heating	19.3	21	18	25	41	
	14:00pm	Through Heating	119	27	23	40.5	115	
	17:00pm	End of Heating	76	26	22	44.2	75	
17.3.11	8:00am	Adsorption	19.3	20	19	23	44	
	8 :30am	Before Heating	19.3	21	18	25	44	
	14:00pm	Through Heating	119	27	23	40.4	120	
	17:00pm	End of Heating	76	26	22	46.9	75	
18.3.11	8:00am	Adsorption	19.3	20	19	23	49	

Remarks :- The quantity of methanol desorbed was found to be 1300 gm on date 15.3.11 as seen from the transparent reservoir which, means 65% of methanol was desorbed. The important noting was that during condensation the pressure increased upto 4psi and then decreased to 1psi. In ideal cycle condensation occurred at constant pressure but actually, it is not so.

- The quantity of methanol desorbed was 250gm on date 16.3.11.
- The quantity of methanol desorbed was 100gm on date 17.3.11
- From, above it can be concluded that the desorption rate decreases because ad sorption not happening in the night. So, the cycle does not work properly.
- When we dismantled the system we found 1500gm methanol in evaporator which clearly indicated that adsorption did not takes place. The reason can be attributed to the leakage of the System and the nonmaintainance of complete vacuum. It is required to make the system hermetically sealed and further work is needed.

A typical one day test data presented here started at 8:15 am local time on 15April 2011 and ended at 8:15am next morning.

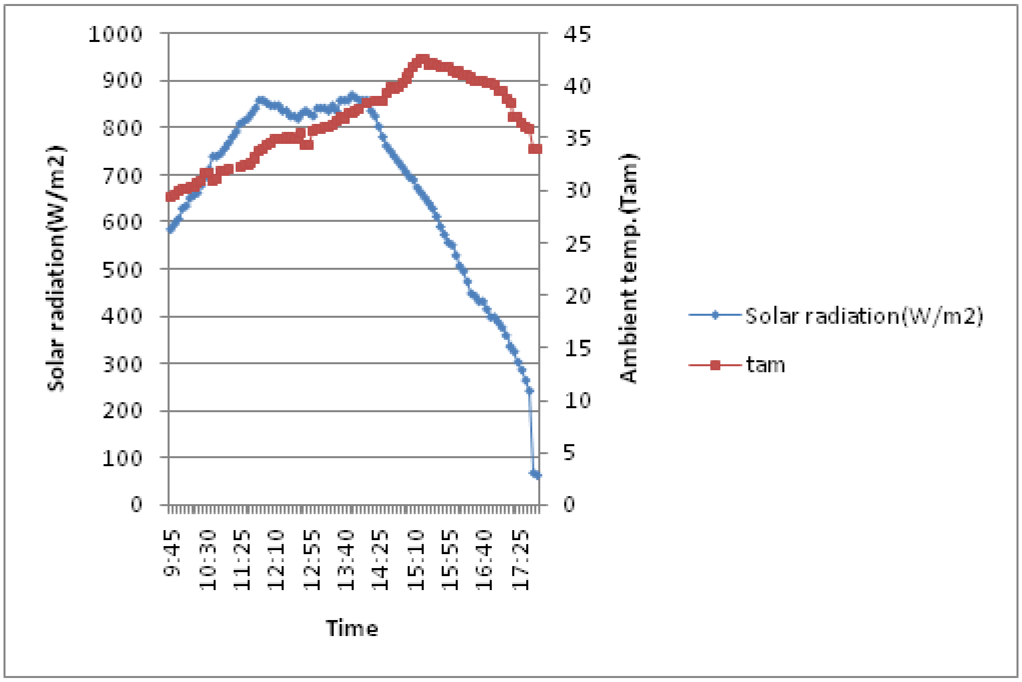


Figure 5.5: Variation of Solar radiation and Ambient temperature Vs. Time

The solar radiation intensity on date (15-03-11) was 19 MJ/m^2 on horizontal surface measured by pyranometer. We calculated Solar radiation intensity on inclined surface which comes around 22 MJ/m^2. Figure.5.5 shows varition of solar radaiton and ambient temperature versus Time.

From fig.5.6 of pressure vs. time we can say that during heating-desorption-condensation period the pressure increased from 40KPa to 118KPa then it remains constant during condensation period. After the peak, pressure begins to drop in the system. During the adsorption process, the evaporation pressure also changes due to variation of temperature inside evaporator tank.

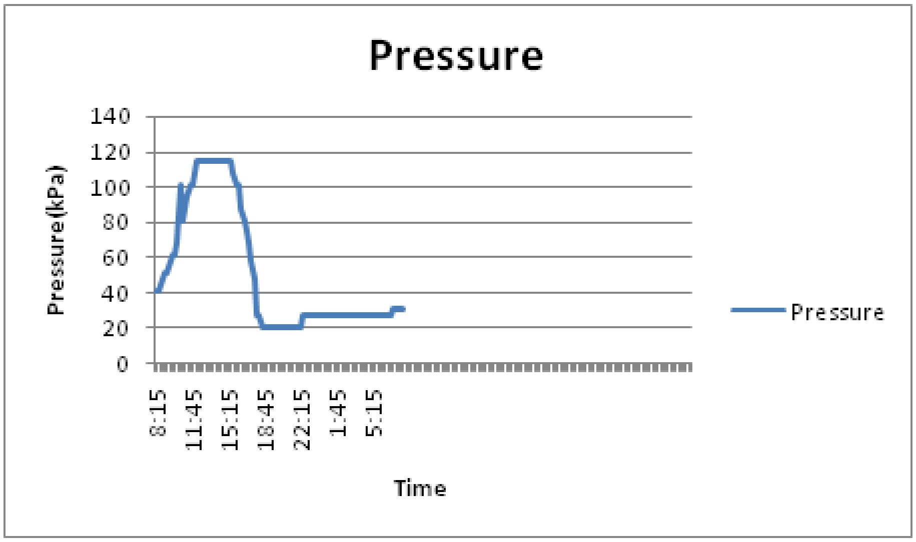


Figure 5.6: Pressure Vs. Time

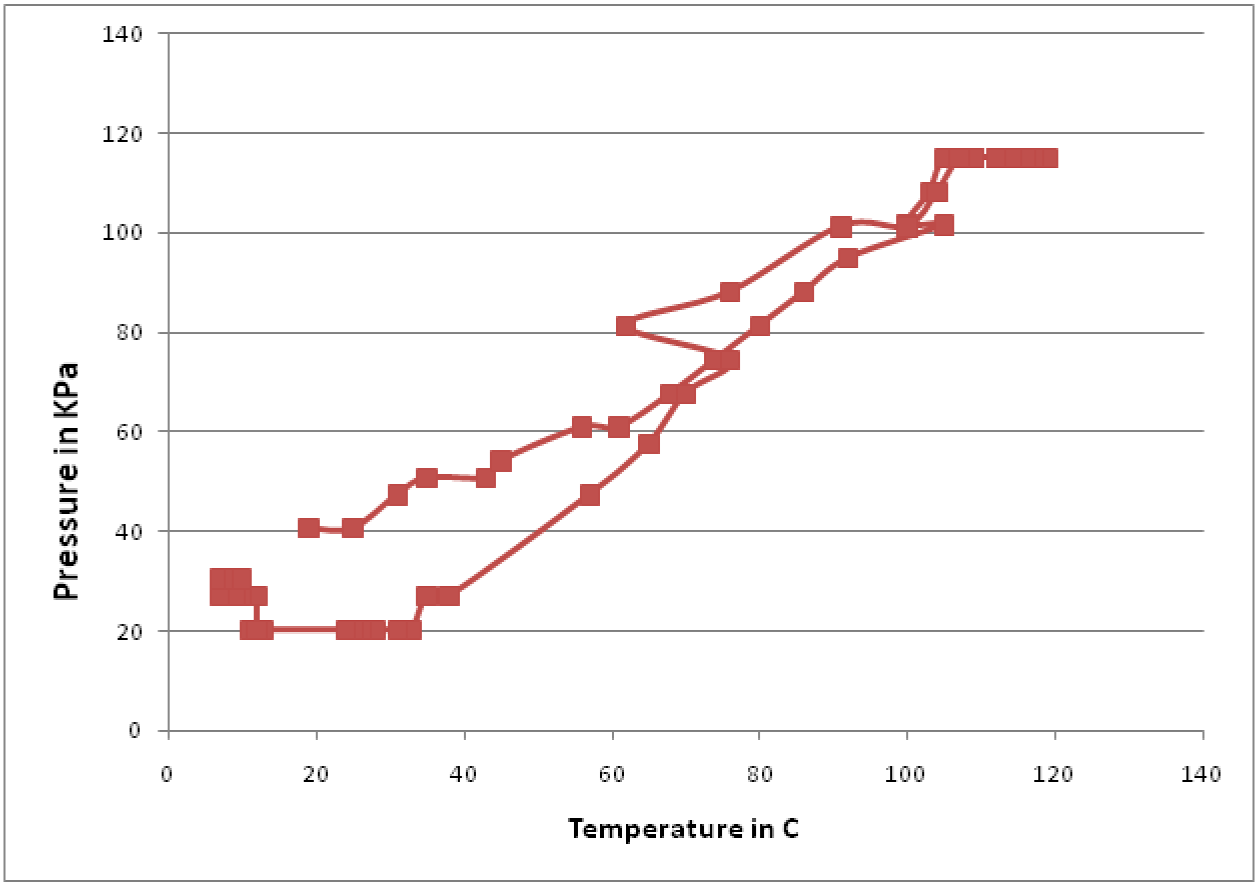


Figure 5.7: Pressure Vs. Temperature

It is seen in fig.5.7 that the pressure in the solar adsorption chiller increases with the increase of adsorbent temperature during the period of heating-desorption-condensation. The refrigerant vapor is condensed as soon as it desorbed from the adsorbent. Moreover, the water temperature inside the condenser tank changes due to ambient temperature fluctuation and the release of condensation heat. Hence the condensation process does not follow an isobaric path.The condensation pressure reaches its maximum of about 118 kPa at 12:25pm and remains almost constant from about 12:25pm to14:45pm. After the peak, the pressure in solar adsorption chiller begins to drop. During the adsorption process, the evaporation pressure also changes due to variation of temperature inside evaporator tank.

Chapter 6

Conclusion and Future Scope

6.1 Conclusion

It was intended to design a solar adsorption refrigeration system to produce 2 kg of ice during 12 hours (8 pm to 8 am) i.e during off Sun shine hours which is a favorable period for the adsorption system. For the said solar adsorption system cooling capacity was calculated as 27W. Assuming maximum desorption of 65%, 2 kg of methanol was required for the system. Activated carbon required was 7 kg. For activated carbon of 7 Kg ,the collector area required was 0.90 m^2. The system was fabricated and tested exhaustively under the Sun. During testing it was observed that the solar collector area was sufficient for desorption of required amount of methanol. The pressure after condensation was also found satisfactory. The best condensation happened in the pressure range of 101 kPa to 120 kPa.

The top plate temperature of adsorber bed reached up to 130 $°C$ with reflector and 110 °C without reflector. In general 15% rise in temperature with reflector without tracking was observed. Reflector was particularly used when incoming solar radiation intensity was low.

However, in this study the required cooling was not observed. For adsorption to take place pressure of the tune of 20 kPa and less was essential. In the present study due to improper sealing of the system, required vacuum was not maintained.

The performance of the adsorption system depends highly on the adsorption pairs, solar intensity, and vacuum within the system. It is recommended that this kind of solar powered adsorption chiller be used for regions having abundant sunshine during daytime and lower temperature during night.

6.2 Future Scope

The system will be required to be well fabricated and well sealed for getting good results. A high performance vacuum pump can be used with special liquid Nitrogen cold trap. With such instruments it is easier to decrease pressure to the lowest value without losing any methanol vapor. Different types of activated carbon such as activated carbon fiber, or consolidate activated carbon, which have higher adsorption capacity may be used to get better results.

Bibliography

[1] Wimolsiri Pridasawas, (2006) . Solar-Driven Refrigeration Systems with Focus on the Ejector Cycle, Royal Institute of Technology, KTH, Denmark. 1, 4, 8, 14

[2] Althous, A., Turnquist, C., and Brancciano, A.(1988). Modern Refrigeration and Airconditioning, 5th edition, Goodheart-Willcox, INC., USA. 2

[3] Wimolsiri Pridasawas, and Teclemariam Nemariam. (2003), solar cooling, Assignment for Ph.D. Course: Solar Heating, Technical University of Denmark (DTU). 2, 5, 10

[4] http://www.powerfromthesun.net/Book/chapter06/chapter06.html 31

[5] Zigler F. (1999). Recent developments and future prospects of sorption heat pump systems. International Journal of Thermals;38:191–208. 16, 23

[6] Miller EB. (1929). The Development of SilicaGel, Refrigerating Engineering, The American Society of Refrigerating Engineers. 16

[7] A.O. Dieng, R.Z. Wang, (2001) Literature review on solar adsorption technologies for ice- purposes and recent developments in solar technology, Renewable and Sustainable Energy Reviews 5313–342 17, 25

[8] Stephan K, Krauss R. (1992).Regulated CFCs and their alternatives. In: Meunier F, editor. Proceedings: Solid Refrigeration Symposium. Paris: Ministere de la Recherche et de L'Espace,:32–43. 17

[9] Pons, M., and Guilleminot, J. J., "Design of an Experimental Solar-Powered, Solid-Adsorption Ice Maker," Journal of Solar Energy Engineering, vol. 108, no. 4, pp. 332-337, 1986. 17

[10] Wang, W., Wang, R. Z., Xu, Y. X., Wu, J. Y., and Gui, Y. B., "Investigation on Adsorption Refrigeration with a Single Adsorbent Bed," International Journal of Energy Research, vol. 22, no. 13, pp. 1157-1163, 1998. 17

[11] Wang, R. Z., "Performance Improvement of Adsorption Cooling by Heat and Mass Recovery Operation," International Journal of Refrigeration, vol. 24, no. 7, pp. 602-611, 2001. 18

[12] . Anyanwu E E, Ezekwe C I, ”Design, construction and test run of a solid adsorption solar refrigerator using activated carbon/methanol, as adsorbent/adsorbate pair.” Energy Conversion and Management 44 (2003) 2879–2892 18

[13] H.L. Luo , Y.J. Dai , R.Z. Wang , Runsheng Tang , M. Li, “Year round test of a solar adsorption ice maker in Kunming, China, Energy Conversion and Management 46 (2005) 2032–2041 18

[14] M. Pons, J.J. Guilleminot, (1986).Design of an experimental solarpowered, solid-adsorption ice maker, Transactions of the ASME, Journal of Solar Energy Engineering 108 (November) 332–337. 19, 27, 65

[15] Khattab N M, (2004),A novel solar-powered adsorption refrigeration module, Applied Thermal Engineering 24, 2747–2760 27, 28

[16] Critoph R E, (1994).An ammonia carbon solar refrigeration for vaccine cooling, Renewable Energy 5 (Part I) 502–508 20

[17] F. Meunier, (1994). Sorption solar cooling, Renewable Energy 5 (Part I) 422–429. 20

[18] Leite, APF. (1998). Thermodynamic analysis and modeling of an adsorption-cycle system for refrigeration from low- grade energy sources. Journal of the Brazilian Society of Mechanical Sciences;20(3):301-24. 21

[19] Meunier F, Douss N. (1990).Performance of adsorption heat pumps: active-carbon-methanol and zeolite-water pairs. In: Trans. ASHRAE Meeting, Saint Louis, USA.. p. 491-8. 21

[20] Dubinin MM, Astakhov VA. (1971) Development of the concept of volume filling of micropores in the adsorption of gases and vapors by microporous adsorbents. Washington, DC, USA: American Chemical Society, 21

[21] Leite, Antonio Pralon Ferreira, Michel Daguenetb. (2000) Performance of a new solid adsorption ice maker with solar energy regeneration. Energy Conversion & Management 41 1625-1647 20, 21, 27

[22] Anyanwu E E, (2004). Review of solid adsorption solar refrigeration II :An overview of the principles and theory, Energy Conversion and Management 45 (2004) 1279–1295 24, 26

[23] Critoph R E ,activated carbon adsorption cycles for refrigeration and heat pumping. Engineering Department, University of Warwick, Coventry, CV4 7AL. U.K 24, 25, 27

[24] L.W.Wang, R.Z.Wang, R.G.Oliveira, "A review on adsorption working pairs for refrigeraton" Renewable and sustainable energy reviews 13(2009) 518-534 26

[25] M. Li, R.Z. Wang. (2002) A study of the effects of collector and environment parameters on the performance of a solar powered solid adsorption refrigerator, Renewable Energy, 27 369–382. 30, 32

[26] Gacciolaa G, Restuccia G. (1994) Progress on adsorption heat pump, Heat Recovery System & CHP; 14(4):409–20. 31

[27] Wang R Z. Adsorption refrigeration research in Shanghai Jiao Tong University. Renewable Sustainable Energy Rev 2001; 5(1):1–37. 34

[28] Wang R Z. Performance improvement of adsorption cooling by heat and mass recovery operation. Int J Refrigeration 2001;24:602–11. 34

[29] K. Sumathy, K.H. Yeung, Li Yong. (2003). Technology development in the solar adsorption refrigeration systems, Progress in Energy and Combustion Science 29 301–327. 36, 42

[30] Shelton S V, Wepfer WJ. Solid–vapor heat pump technology. In: Proceedings of the IEA Heat Pump Conference, Japan: Tokyo; 1990. p. 525–35. 36

[31] . Critoph R E. Forced convection adsorption cycles. Appl Thermal Engng 1998;18:799–807. 38

[32] . Critoph R E. Forced convection adsorption cycle with packed bed heat regeneration. Int J Refrigeration 1999;22:38–46. 38

[33] . http://www.powerfromthesun.net/index.htm, chapters(1), 44

[34] ://www.powerfromthesun.net/index.htm, chapters(2), June (2007) 44

[35] . http://www.mapsofindia.com/india-climate.html 47

[36] Solar Radiation Hand Book (2008), Typical Climatic Data for Selected Radiation Stations (The Data Period Covered : 1986-2000), A joint Project of Solar Energy Centre, MNRE Indian Metrological Department 49

[37] Wang L W, Wu J Y, Wang R Z, “Study of the performance of activated carbon-methanol adsorption systems concerning heat and mass transfer”, Applied Thermal Engineering 23(2003)1605-1617 51

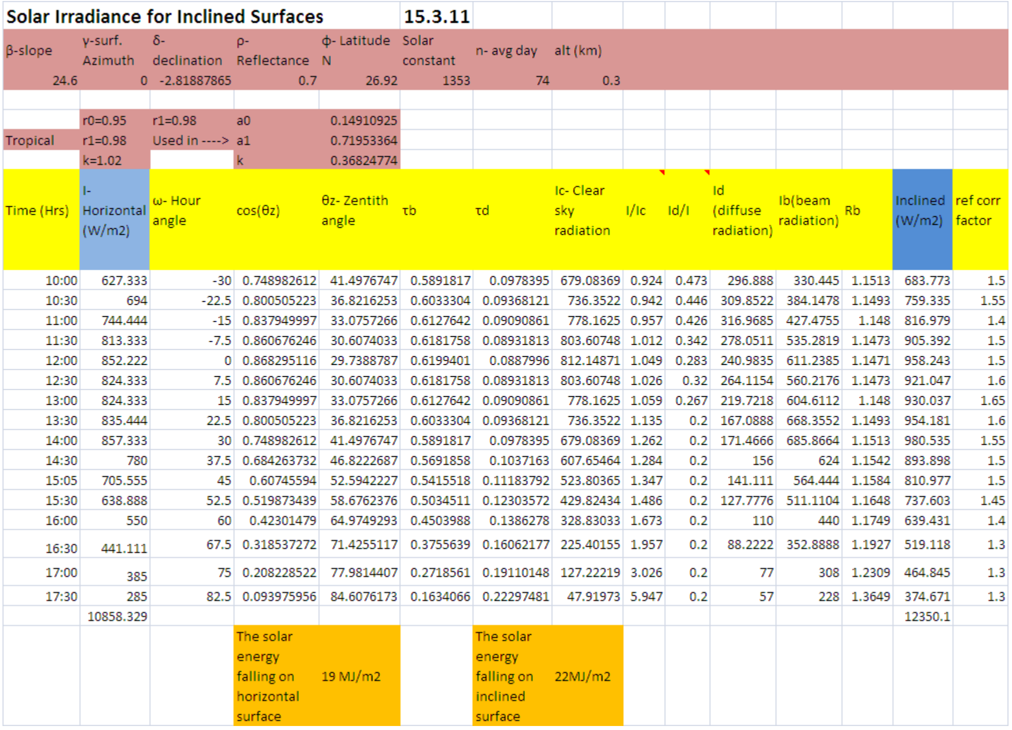
[38] Heat exchangers by Sadic Kakac and Hongtan Liu, CRC Press. 56

[39] Solar Engineering of Thermal Processes, Second edition by Duffie and Beckman, John Wiley & Son 52, 53

[40] Li M., R.Z. Wang, Y.X. Xu, J.Y. Wu, A.O. Dieng, (2005). Experimental study on dynamic performance analysis of a flat-plate solar solid-adsorption refrigeration for ice maker, Applied Thermal Engineering 25 1614–1622. 64

Appendix A

Calculation of solar intensity falling on inclined surface



Solar Irradiance for Inclined Surfaces					**15.3.11**									
β-slope	γ-surf. Azimuth	δ- declination	ρ- Reflectance	ϕ- Latitude N	Solar constant	n- avg day	alt (km)							
24.6	0	-2.81887865	0.7	26.92	1353	74	0.3							
	r0=0.95	r1=0.98	a0	0.14910925										
Tropical	r1=0.98	Used in ---->	a1	0.71953364										
	k=1.02		k	0.36824774										
Time (Hrs)	I- Horizontal (W/m2)	ω- Hour angle	cos(θz)	θz- Zentith angle	τb	τd	Ic- Clear sky radiation	I/Ic	Id/I	Id (diffuse radiation)	Ib(beam radiation)	Rb	Inclined (W/m2)	ref corr factor
10:00	627.333	-30	0.748982612	41.4976747	0.5891817	0.0978395	679.08369	0.924	0.473	296.888	330.445	1.1513	683.773	1.5
10:30	694	-22.5	0.800505223	36.8216253	0.6033304	0.09368121	736.3522	0.942	0.446	309.8522	384.1478	1.1493	759.335	1.55
11:00	744.444	-15	0.837949997	33.0757266	0.6127642	0.09090861	778.1625	0.957	0.426	316.9685	427.4755	1.148	816.979	1.4
11:30	813.333	-7.5	0.860676246	30.6074033	0.6181758	0.08931813	803.60748	1.012	0.342	278.0511	535.2819	1.1473	905.392	1.5
12:00	852.222	0	0.868295116	29.7388787	0.6199401	0.0887996	812.14871	1.049	0.283	240.9835	611.2385	1.1471	958.243	1.5
12:30	824.333	7.5	0.860676246	30.6074033	0.6181758	0.08931813	803.60748	1.026	0.32	264.1154	560.2176	1.1473	921.047	1.6
13:00	824.333	15	0.837949997	33.0757266	0.6127642	0.09090861	778.1625	1.059	0.267	219.7218	604.6112	1.148	930.037	1.65
13:30	835.444	22.5	0.800505223	36.8216253	0.6033304	0.09368121	736.3522	1.135	0.2	167.0888	668.3552	1.1493	954.181	1.6
14:00	857.333	30	0.748982612	41.4976747	0.5891817	0.0978395	679.08369	1.262	0.2	171.4666	685.8664	1.1513	980.535	1.55
14:30	780	37.5	0.684263732	46.8222687	0.5691858	0.1037163	607.65464	1.284	0.2	156	624	1.1542	893.898	1.5
15:05	705.555	45	0.60745594	52.5942227	0.5415518	0.11183792	523.80365	1.347	0.2	141.111	564.444	1.1584	810.977	1.5
15:30	638.888	52.5	0.519873439	58.6762376	0.5034511	0.12303572	429.82434	1.486	0.2	127.7776	511.1104	1.1648	737.603	1.45
16:00	550	60	0.42301479	64.9749293	0.4503988	0.1386278	328.83033	1.673	0.2	110	440	1.1749	639.431	1.4
16:30	441.111	67.5	0.318537272	71.4255117	0.3755639	0.16062177	225.40155	1.957	0.2	88.2222	352.8888	1.1927	519.118	1.3
17:00	385	75	0.208228522	77.9814407	0.2718561	0.19110148	127.22219	3.026	0.2	77	308	1.2309	464.845	1.3
17:30	285	82.5	0.093975956	84.6076173	0.1634066	0.22297481	47.91973	5.947	0.2	57	228	1.3649	374.671	1.3
	10858.329												12350.1	
			The solar energy falling on horizontal surface	19 MJ/m2		The solar energy falling on inclined surface	22MJ/m2							

Figure A.1: Calculation of solar intensity on an inclined surface