A PROJECT REPORT

ON

"VAPOUR ABSORPTION REFRIGERATION SYSTEM"

Submitted by

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In partial fulfillment for the award of the Degree

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UNDER THE GUIDANCE

Of

Prof. MOHD SIRAZUDDIN KHAN

DEPARTMENT OF MECHANICAL ENGINEERING

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CERTIFICATE

This is to certify that the project entitled

"VAPOUR ABSORPTION REFRIGERATION SYSTEM"

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APPROVAL OF DISSERTATION

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ABSTRACT

The improvement in the quality of life has increased the demand for Refrigeration systems throughout the world. The use of high-grade energy for the operation of these systems is associated with Green House Gas emissions and thermal pollution in the form of waste heat besides depletion of fossil fuels. In this context, vapour absorption refrigeration systems are looked upon with renewed interest as they work on heat operated system with environment friendly working fluids. Heat rejection capacities of these systems are higher than that of electrically operated vapour compression systems. Hence, considerable advantage lies in the use of air-cooled absorber and condenser especially with reference to the small capacity vapour absorption refrigeration units. This eliminates the necessity of a cooling tower and the associated maintenance issues. Utilizing the generator-absorber heat exchange principle in the conventional ammonia-water system reduces the generator heat input and thereby enhancing the system coefficient of performance. This thesis presents both the theoretical and experimental investigations on the air-cooled modified generator-absorber heat exchange based vapour absorption refrigeration system, using ammonia-water as the working fluid.

The feasibility of operating a small capacity (10.5 kW) air-cooled modified generator-absorber heat exchange based vapour absorption refrigeration system using ammonia-water as the working fluid has been established. The performance of the system tested is higher compared to the conventional single effect ammonia-water system. These systems could be employed for cold storage applications in the rural and semi urban areas.

Table of Contents

List of Figures

List of Tables

Chapter 1

INTRODUCTION

1.1 Background

Refrigeration is the process of removing heat from an enclosed space or from a substance for lowering the temperature. Before mechanical refrigeration systems were introduced, ancient people, including the Greeks and the Romans, cooled their food with ice transported from the mountains. Wealthy families made use of snow cellars, pits that were dug into the ground and insulated with wood and straw, to store the ice. In this manner, packed snow and ice could be preserved for months. Stored ice was the principal means of refrigeration until the beginning of the 20^{th} century, and it is still used in some areas. The seasonal harvesting of snow and ice is an ancient practice estimated to have begun earlier than 1000 B.C. A Chinese collection of lyrics from this period known as the Shijing, describes religious ceremonies for filling and emptying ice cellars. However, little is known about the construction of these ice cellars or what the ice was used for. The next ancient society to harvest ice may have been the Jews according to the book of Proverbs, which reads, "As the cold of snow in the time of harvest, so is a faithful messenger to them who sent him." Historians have interpreted this to mean that the Jews used ice to cool beverages rather than to preserve food. Other ancient cultures such as the Greeks and the Romans dug large snow pits insulated with grass, chaff, or branches of trees as cold storage. Like the Jews, the Greeks and Romans did not use ice and snow to preserve food, but primarily as a means to cool beverages. The Egyptians also developed methods to cool beverages, but in lieu of using ice to cool water, the Egyptians cooled water by putting boiling water in shallow earthen jars and placing them on the roofs of their houses at night. Slaves would moisten the outside of the jars and the resulting evaporation would cool the water. The ancient people of India used this same concept to produce ice. The Persians stored ice in a pit called a Yakhchal and may have been the first group of people to use cold storage to preserve food. In the Australian outback before a reliable electricity supply was available where the weather could be hot and dry, many farmers used a "Coolgardie safe". This consisted of a room with hessian "curtains" hanging from the ceiling soaked in water. The water would evaporate and thereby cool the hessian curtains and thereby the air circulating in the room. This would allow many perishables such as fruit, butter, and cured meats to be kept that would normally spoil in the heat. The history of artificial refrigeration began when Scottish professor William Cullen designed a small refrigerating machine in 1755. Cullen used a pump to create a partial vacuum over a container of diethyl ether, which then boiled, absorbing heat from the surrounding air. The experiment even created a small amount of ice, but had no practical application at that time.

1.2 Motivation

Our motivation to make this setup, i.e., vapour absorption refrigeration setup was due to the following reasons.

- Due to non-availability of vapour absorption refrigeration system in our college, we decided to make the setup and use it as our final year project.
- As we are studying the subject Refrigeration and Air Conditioning, we have read about the cycle and thus we got interested in carrying forward it as our project topic.

1.3 Aim and Objective

1.3.1 Aim

The main aim was to build a vapour absorption refrigeration test rig and perform various experiments on it and calculate the COP of it.

1.3.2 Objectives

- To develop a Vapour Absorption Refrigeration test rig for study purposes.
- To study the performance using LiBr-Water solution.
- To conduct a repeatability test to find a deviation in COP.
- To study the difference in the COP's of Vapour Absorption Refrigeration System and Vapour Compression System.

1.4 Problem Definition

We made a vapour absorption refrigeration setup and calculated the COP of this system and later compare it with the vapour compression refrigeration system which was already available in our Refrigeration and Air Conditioning Lab.

1.5 Scope of Work

- Design of a smaller vapour absorption refrigeration unit for academic purposes.
- Study of Lithium Bromide-water as a refrigerant used in the test rig.
- The test rig can be combined with solar energy to demonstrate that solar power can be used for refrigeration purpose, known as S-VARS.
- Further study on the refrigerant used can allow us to reduce cost of refrigeration.
- Results can be compared with two refrigerants combined to run the system.
- Research can be done with other working pair of absorbent and refrigerants like R134 and activated carbon, methanol etc. and their performance can be compared.

Chapter 2

LITERATURE REVIEW

This Chapter involves the survey of research made by different researchers on VARS using various refrigerants to understand the concept of a system and to work on the same to get better performance if possible.

2.1 Paper Research

Here are a few papers we referred to,

Mohammed Aziz et al. conducted an experiment on Design of vapour absorption Refrigeration system in an industry which utilizes steam turbine exhaust gas which contains high amount of thermal energy, the main objective was to make a hypothetical design of the vapour absorption refrigeration system using waste energy. Lithium bromide-water as a refrigerant was selected because it could be driven by gas, solar, geothermal energy which could help in substantially reducing the carbon dioxide emissions and use water as it was abundantly available and cheap. The work input of the pump was neglected as compared to the heat input. Results show that COP minutely increased with the increase in generator and evaporator temperature, this depends largely on the enthalpy difference between the chilled water at inlet and outlet of evaporator. On the contrary it causes a loss of exergy in components which contributes a major role in calculating the efficiency.

S. M. Deng et al. conducted an experimental study on characteristics of an absorber using LiBr-H_2O solution as working fluid, main objective was to find the change in heat transfer coefficient by differing the way of introducing the strong solution of Li-br from the generator to the absorber (Spray method). Here the absorber is an important component in absorption machines and its characteristics have significant effect on the overall efficiency of absorption machines. The results of experimental studies on the characteristics for a falling film absorber which is made up of 24 row horizontal smooth tubes. It shows that while the mass transfer coefficient is increased with the increase of spray density. There is an optimum spray density between 0.005 and 0.055 $kgs^{-1}m^{-1}$ at which the heat transfer coefficient is maximum. The effect of cooling water inlet temperature on absorber's performance is significant. When the inlet temperature of cooling water decreases from 32°c to 30°c, the heat flux of absorber increases by more than 17%. The inlet solution concentration of lithium bromide is one of the many important parameters that influence heat transfer coefficients. When other conditions such as solution temperature or flow characteristics remain unchanged, heat transfer coefficient is increased with the increase of the inlet concentration. In practical design, using the strong solution as absorbent is advantageous in order to enhance the heat transfer and decrease the solution pump power. After this, the heat transfer coefficient slightly drops when the spray density is increased. Therefore, to select an appropriate spray density is important in the practical design of an absorption machine.

G. A. Florides et al. conducted an experiment which involved the design and construction of Li-br–water absorption machine**,** main objective was to find the difference between the absorber LiBr inlet and outlet percentage ratio, the coefficient of performance of the unit in relation to the generator temperature, the efficiency of the unit in relation to the solution heat exchanger area and the solution strength effectiveness in relation to the absorber solution outlet temperature are examined. Single pass, vertical tube heat exchangers had been used for the absorber and for the evaporator. The solution heat exchanger was designed as a single pass annular heat exchanger. The condenser and the generator were designed using horizontal tube heat exchangers. The analysis shows that the greater the difference between the absorber LiBr inlet and outlet percentage ratios is, the smaller will be the mass circulating in the absorber. To keep the cycle running at a specified stage, the temperature at the exit of the absorber has to be maintained at a lower level when the absorber exit LiBr percentage ratio is lower. Considering that the pressures and temperatures at other points of the unit are kept constant, the COP of the unit is lowered when the generator temperature is increased, leading to an increase of the generator pressure. The solution heat exchanger increases the efficiency of the unit. The greater the heat exchanger area, the greater its effect is. Finally, when checking the solution strength effectiveness for a constant difference of 6% between the absorber inlet LiBr percentage ratio and absorber outlet ratio, it was found that a smaller percentage ratio in LiBr solutions would have slightly better results. A reasonable temperature at the exit of the absorber would be around 30 °C.

B. Babu et al. conducted an experiment on Performance Analysis of Lithium-bromide water absorption refrigeration system using waste heat of boiler flue gases where the main theme is to utilize the waste heat of the flue gases generated in thermal power stations. Before leaving these gases to the atmosphere through the chimney necessary mass of flue gases is by passed and is made to deliver it generator so as to run the vapour absorption refrigeration system there by conserving the energy. The aim of the project is to perform analysis on absorption refrigeration system using lithium-bromide and water as refrigerant and to find out the influence of operating temperatures on the thermal loads of components and their co-efficient of performance. The heat load on the generator decreases by 3336.03kJ/kg with the increase in generator temperature of 25°C and 452kJ/kg with the increase in evaporator temperature of 6°C.This decrease in generator heat load causes the increase of C.O.P value by 0.34, when the generator temperature is increased by 35°C and 0.08 with the increase in evaporator temperature of 6°C. The heat load on the generator increases by 3002.3kJ/kg as the condenser temperature increased by 15°C and 1731.3kJ/kg as absorber temperature increased by 15°C. The increase in the generator heat load decreases the C.O.P value by 0.38, when the condenser temperature is increased by 15°C and 0.23 when the absorber temperature is increased by 15°C. Thus, this analysis provides that the operating temperatures of condenser and absorber has to be maintained less than 40°C, evaporator temperature has to be more than 10ºc and the generator temperature not exceeding 85ºC so as to run the absorption system efficiently during the utilization of heat from the waste flue gases and provide cooling effect in the boiler control room and therefore conserving the energy.

Neeraj Kumar et al. conducted an experiment which involved the design and construction of a Solar Vapour Absorption System using Li-br–water. Aim of the experiment was to develop a model which could predict the COP of the system which could run on solar energy. The heat was supplied to generator by solar collector which heated water running through the generator, herby heating the refrigerant. The Paper states that with the increase in generator and evaporator temperature the COP increases significantly, as the condenser temperature drops it causes less heat transfer in the condenser which causes an increase in enthalpy of refrigerant at condenser outlet, this causes decreases in cooling capacity indirectly affecting the COP. Further conduction of tests indicated that the temperature range of 65°C to 80°C was suitable to get absorption system work efficiently with increased performance.

M. Mazloumi et al. simulated an experiment which involved Li-br–water absorption cooling system using parabolic trough collector. The main aim of this research was to simulate solar single effect lithium-bromide water absorption cooling system that could be used in households with a peak load of 17. 5kW.The software used for the simulation was Transys. This experiment conducted concludes that flat plate or evacuated plate collectors are impractical to cool places with high amount of cooling load, the parabolic trough collector obtains more solar energy which causes the system to operate earlier. The results showed that the collector mass flow rate has a negligible effect on the minimum required collector area, but it has a significant effect on the optimum capacity of the storage tank. The minimum required collector area was about 57.6 m^2, which could supply the cooling loads for the sunshine hours of the design day for July. The operation of the system has also been considered after sunset by saving solar energy.

S. Alizadeh et al. conducted an experiment which involved the design and optimization of an absorption refrigeration system operated by solar vapour, this experiment was conducted with a fixed evaporator temperature to compare the two cycles of ammonia water system and lithium-bromide water system. Results show that the water-lithium bromide system is simpler than the ammonia-water system and it operates at a higher cooling ratio (ratio of energy removed from the surroundings during the refrigeration phase to that supplied to generator during regeneration phase) and heat exchanger parameter for the same conditions. Paper states that as the generator temperature increases beyond a point the condenser and absorber temperature decreases.

2.2 Observations from the literature survey

- VARS test rig operated in vacuum gives best results in COP.
- If operating temperature of condenser and absorber should be maintained less than 40°C, evaporator temperature greater than 10°C and generator temperature up to 85°C, this results in improved performance of the setup.
- Addition of a heat exchanger between the absorber and generator further improves performance of the system
- As circulation ratio (ratio of mass concentration of weak solution to the difference in mass concentration of strong and weak solution) increases COP decreases hence low circulation ratio is preferred.

As generator temperature and pressure increases COP decreases.

Chapter 3

THEORY OF REFRIGERATION SYSTEM

3.1 Introduction of Refrigeration System

Refrigeration is the process of removing heat from an enclosed space or from a substance for the purpose of lowering the temperature. Before mechanical refrigeration systems were introduced, ancient people, including the Greeks and the Romans, cooled their food with ice transported from the mountains. Wealthy families made use of snow cellars, pits that were dug into the ground and insulated with wood and straw, to store the ice. In this manner, packed snow and ice could be preserved for months. Stored ice was the principal means of refrigeration until the beginning of the 20th century, and it is still used in some areas. Basically, there are two ways with which refrigeration can be achieved:

1. Natural Refrigeration.
2. Artificial Refrigeration.

3.1.1 Natural Refrigeration:

In olden days, natural means achieved refrigeration with the use of ice and evaporative cooling.

In earlier times, the ice was

- Transported from colder regions
- Harvested in winter and stored for use
- Made during the night by Radiative cooling

Nocturnal Ice Making:

In India before the invention of artificial refrigeration technology, ice making by nocturnal cooling was common. The apparatus consisted of a shallow ceramic tray with a thin layer of water, placed outdoors with a clear exposure to the night sky. The bottom and sides were insulated with a thick layer of hay. On a clear night the water would lose heat by radiation upwards. Provided the air was calm and not too far above freezing, heat gain from the surrounding air by convection would be low enough to allow the water to freeze by dawn.

Evaporative Cooling:

Reduction in temperature resulting from the evaporation of a liquid, which removes latent heat from the surface from which evaporation takes place. This process is employed in industrial and domestic cooling systems and is also the physical basis of sweating. In India during olden times, Water was cooled by this method by keeping it in earthen pots, in which the water would evaporate through minute pores and thus cool it.

Cooling using salts:

When salt is added to water it lowers the freezing point of water, and salt allows water to exist as a liquid at a temperature lower than 0°C. This type of cooling has limited use, since the dissolved salts can only be removed by heating.

3.1.2 Artificial Refrigeration:

Refrigeration today is mostly produced by artificial means. Some of the artificial means are

- Cyclic refrigeration
- Non-Cyclic Refrigeration
- Thermoelectric Refrigeration
- Magnetic Refrigeration

3.2 Classifications of Refrigeration System

We will focus on the two important types of Cyclic Refrigeration,

1. Vapour Compression Refrigeration
2. Vapour Absorption Refrigeration

3.2.1 Vapour Compression Refrigeration:

The components of a vapour-compression refrigeration cycle are a compressor, condenser, expansion valve, and evaporator as shown in the fig 1.1. A low pressure, low temperature liquid is converted to vapour in the evaporator, thus absorbing heat from the refrigerated space and keeping that space cool. The fluid is driven around the cycle by the compressor, which compresses the low temperature, low pressure vapour leaving the evaporator to high pressure, high temperature vapour. That vapour is condensed to liquid in the condenser, thus giving off heat at a high temperature to the surrounding environment. Finally, the high pressure, high temperature liquid leaving the condenser is cooled and reduced in pressure by passing it through an expansion valve. The rate of work input to the compressor is most of the power requirement to run the refrigeration system. Power will be needed to drive one or more fans, but their power requirement will be small in comparison with that needed to drive the compressor.

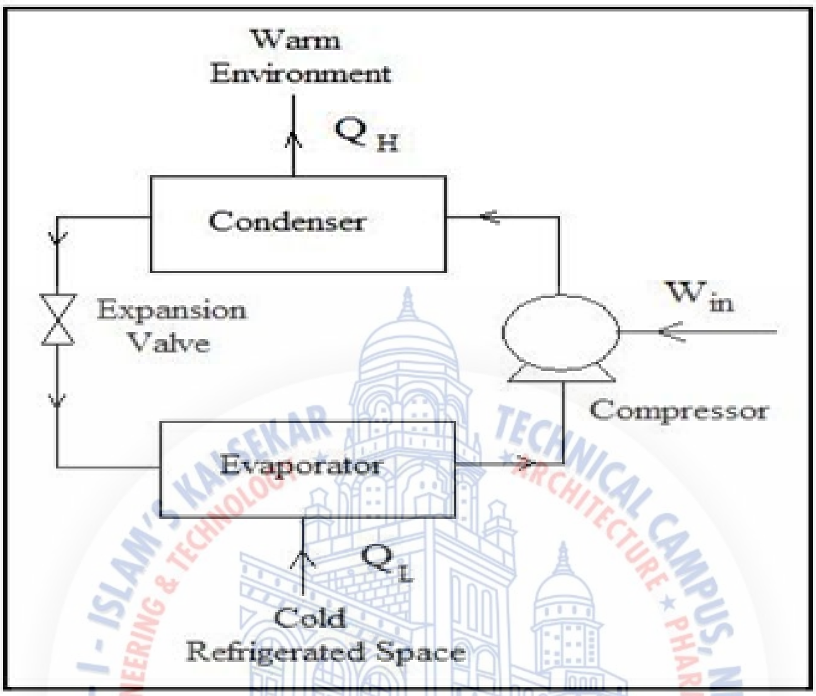

Figure 1.1: Vapour Compression Cycle

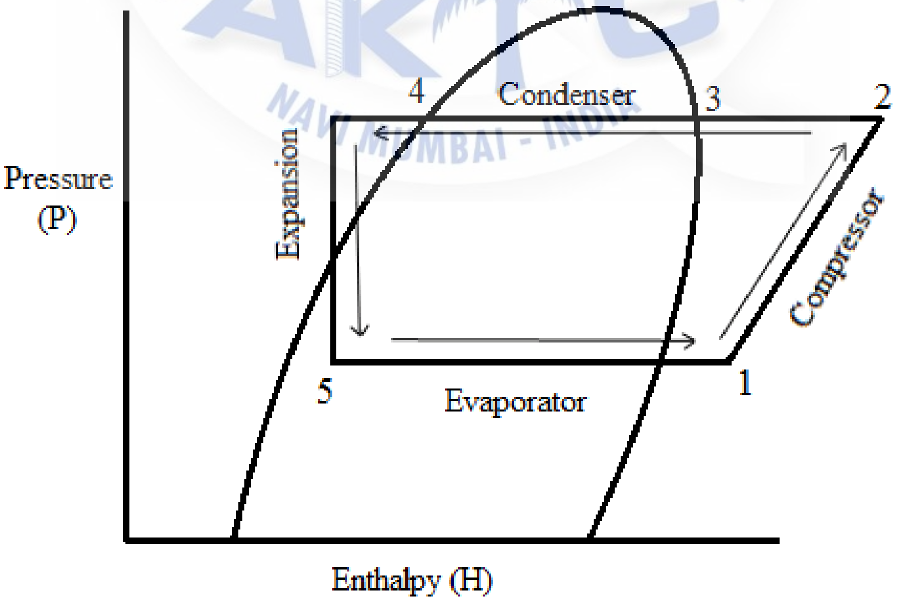

Figure 1.2: Pressure-enthalpy diagram for Vapour Compression Cycle

The following processes are shown in the p-h diagram:

Compression:

In this stage, the refrigerant enters the compressor as a gas under low pressure and having a low temperature. Then, the refrigerant is compressed adiabatically, so the fluid leaves the compressor under high pressure and with a high temperature. In the figure 1.2, 1-2 shows Compression.

Condensation:

In the fig 1.2, 2-4 shows Condensation process. The high pressure, high temperature gas releases heat energy and condenses. The condenser is in contact with the hot reservoir of the refrigeration system. (The gas releases heat into the hot reservoir because of the external work added to the gas.) The refrigerant leaves as a high-pressure liquid.

Throttling:

The liquid refrigerant is pushed through a throttling valve, which causes it to expand. As a result, the refrigerant now has low pressure and lower temperature, while still in the liquid phase. (The throttling valve can be either a thin slit or a plug with holes in it. When the refrigerant is forced through the throttle, its pressure is reduced, causing the liquid to expand.). Process 4-5 in fig 1.2 shows the process of expansion.

Evaporation:

The low pressure, low temperature refrigerant enters the evaporator, which is in contact with the cold reservoir. Because a low pressure is maintained, the refrigerant is able to boil at a low temperature. So, the liquid absorbs heat from the cold reservoir and evaporates. The refrigerant leaves the evaporator as a low temperature, low pressure gas and is taken into the compressor again, back at the beginning of the cycle. From the fig 1.2 the process 5-1 shows Evaporation.

3.2.2 Vapour Absorption Refrigeration:

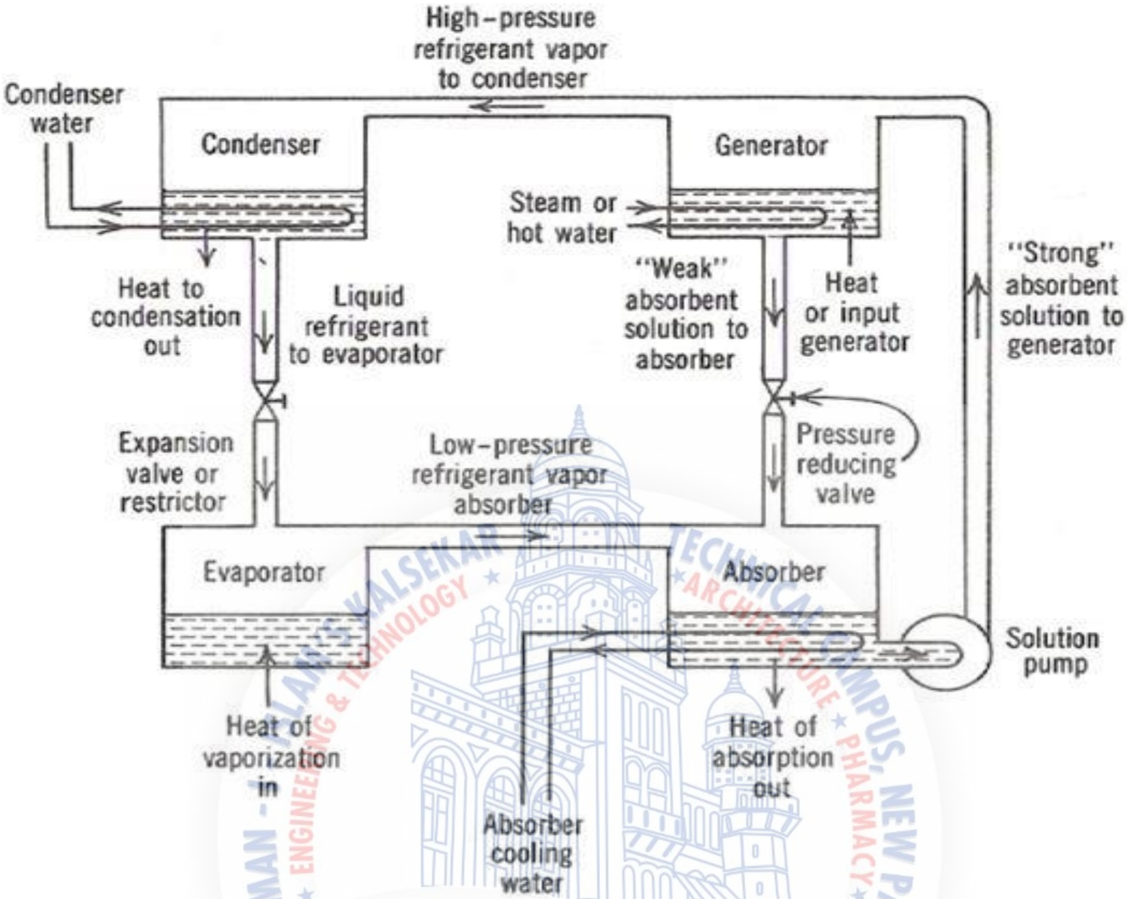

Figure 1.3: A Vapour Absorption Refrigeration Cycle

The fig 1.3 shows a Vapour Absorption Refrigeration system, the vapour absorption refrigeration system comprises of a generator, an absorber, an evaporator and a condenser. In the vapour absorption system, the refrigerant used is ammonia, water or lithium bromide. The refrigerant produces cooling effect in the evaporator and releases the heat to the atmosphere via the condenser. The absorber and the generator perform a function like that of the compressor in the Vapour Compression cycle. The absorbent enables the flow of the refrigerant from the absorber to the generator. Another major difference is the method in which the energy input is given to the system. In the vapour compression system, the energy input is given in the form of the mechanical work from the electric motor. In the vapour absorption system, the energy input is given in the form of the heat.

The absorption cooling cycle takes place in three phases:

Evaporation:

A liquid refrigerant evaporates in a low partial pressure environment, thus extracting heat from its surroundings (e.g. the refrigerator's compartment). Because of the low partial pressure, the temperature needed for evaporation is also low.

Absorption:

The new gaseous refrigerant is absorbed by another liquid (e.g. a salt solution) in the absorber.

Regeneration:

The refrigerant-saturated liquid is heated, causing the refrigerant to evaporate out. The hot gaseous refrigerant passes through a heat exchanger, transferring its heat outside the system (such as to surrounding ambient-temperature air), and condenses. The condensed (liquid) refrigerant supplies the evaporation phase.

3.3 Vapour Absorption Refrigeration System

3.3.1 Simple vapour absorption system

The vapor absorption refrigeration system comprises of all the processes in the vapour compression refrigeration system like compression, condensation, expansion and evaporation. In the vapour absorption system, the refrigerant used is ammonia, water or lithium bromide. The refrigerant gets condensed in the condenser and it gets evaporated in the evaporator. The refrigerant produces cooling effect in the evaporator and releases the heat to the atmosphere via the condenser. There is no compressor in the vapour absorption refrigeration system.

3.3.2 Components used in vapour absorption refrigeration system

A simple vapour absorption refrigeration system consists of the following parts:

Generator:

The solution of aqua-ammonia received from the absorber is heated by some external sources such as electric heater or gas flame. Because of this heating the ammonia solution gets separated into ammonia vapour at high pressure and hot weak ammonia which mostly consists of water.

Condenser:

Condenser converts the high-pressure ammonia vapour received from the generator into high pressure ammonia liquid. This process is done by means of circulating cool water.

Expansion valve or throttle valve:

The expansion that takes place in the expansion valve is throttling. The high-pressure ammonia liquid is expanded to low pressure low temperature ammonia in the expansion valve.

Evaporator:

Evaporator, also called cold chamber, is the actual freezing. The ammonia refrigerant passing through the evaporator absorbs the heat and evaporates.

Absorber:

The function of the absorber is to absorb low pressure ammonia vapour from the evaporator and weak ammonia solution from the generator. The purpose of the absorber is to make this mixture into a string solution, which is pumped back to the generator.

Heat Exchanger:

It is used to transfer the heat from strong ammonia solution to the weak solution.

Pump:

It is used to circulate the strong ammonia through the heat exchanger. The pump increases the pressure of the solution.

3.4 Refrigerants

A refrigerant is a substance or mixture, usually a fluid, used in a heat pump and refrigeration cycle. In most of the cycles it undergoes phase change from liquid to gas or gas to liquid. It could also be termed as a chemical used in cooling mechanism, such as an air conditioner or refrigerator, as the heat is carried it changes phase and completes the refrigeration cycle. Most common refrigerants used are chlorofluorocarbons (CFC's) but they are being phased out as the degrade the environment.

3.4.1 Ammonia

Ammonia has been used as a refrigerant since the 19th century. All those who are involved in food preservation and industrial process plants know ammonia as refrigerant of choice due to its unmatched thermodynamic properties. Anhydrous ammonia is a clear liquid that boils at a temperature of -33°C. In refrigeration systems, the liquid is stored in closed containers under pressure. When the pressure is released, the liquid evaporates rapidly, generally forming an invisible vapour or gas. The rapid evaporation causes the temperature of the liquid to drop until it reaches the normal boiling point. A similar effect occurs when water evaporates off the skin, thus cooling it. Therefore, ammonia is used in refrigeration systems.

Ammonia cannot be used as a refrigerant when copper is used in the test rig because in the presence of water ammonia becomes ammonium hydroxide and this reacts with Copper to form cupric oxide. Common metals are not affected by anhydrous ammonia but even a little water or moisture will cause ammonia to react with copper and corrode it. Ammonia is highly poisonous to human beings, so it may cause a health hazard. Filling of ammonia requires a highly skilled operator and to operate at high pressure the system must be leak proof.

3.4.2 Lithium-Bromide:

Lithium Bromide (Li-Br) consists of certain percentages of Lithium and Bromine. Lithium is a soft, light, silver-white, highly reactive metallic element of the group 1 from the periodic table with atomic number 3 whereas Bromine is a chemical element belonging to the halogen category with atomic number 35 and is the third lightest halogen. It has a fuming red-brown color at room temperatures which can evaporate readily at ease. But Lithium-Bromide is a mixture of both lithium and bromine which is white in color and has a bitter taste which is completely soluble in water, alcohol, and glycol. It is used as an operating medium in air conditioners and refrigerators due to its hygroscopic property. It is also used for sedation and has a hypnotic characteristic used for brazing and welding fluxes.

In a Lithium Bromide-Water vapour absorption refrigeration system, water is used as the refrigerant while Lithium Bromide (LiBr) is used as the absorbent. In the absorber, the lithium bromide absorbs the water refrigerant, creating a solution of Water and Lithium Bromide. This solution is pumped by the pump to the generator where the solution is heated. The water refrigerant gets vaporized and moves to the condenser where it is cooled while the Lithium Bromide flows back to the absorber where it further absorbs water coming from the evaporator.

Some Special features of the LiBr-Water combination used a refrigerant:

- The water used as the refrigerant in the absorption refrigeration system means the operating pressures in the condenser and the evaporator must be very low. Even the difference of pressure between the condenser and the evaporator must be very low. This can be achieved even without installing the expansion valve in the system, since the drop-in pressure occurs due to friction in the refrigeration piping and in the spray nozzles.
- The capacity of any absorption refrigeration system depends on the ability of the absorbent to absorb the refrigerant, which in turn depends on the concentration of the absorbent. To increase the capacity of the system, the concentration of absorbent should be increased, which would enable absorption of more refrigerant. Some of the most common methods used to change the concentration of the absorbent are: controlling the flow of the steam or hot water to the generator, controlling the flow of water used for condensing in the condenser, and re-concentrating the absorbent leaving the generator and entering the absorber.

Lithium bromide has great affinity for water vapour, however, when the water-lithium bromide solution is formed, they are not completely soluble with each other under all the operating conditions of the absorption refrigeration system. Because of this, the designer must take care that such conditions would not be created where crystallization and precipitation of the lithium bromide would occur.

3.5 Applications of Vapour Absorption Refrigeration System

VARS usually comes in higher capacities (More than 50 TR) until now but china has invented lesser capacity VARS machines (2 TR), so it founds its applications in industries, malls and theatres where we could utilize the exhaust smokes generated by the DG sets and chimneys and can be utilised to superheat the refrigerant, so it is basically energy efficient and economical for places having exhaust smokes.

3.5.1 Applications

Applications of VARS differs from VCRS in many ways:

- Vapour compression refrigeration system is usually applied in small applications like home refrigerators and Small capacity AC's but vapour absorption refrigeration system has to be applied for bigger tonnage plants.
- Vapour compression refrigeration system doesn’t need that much of installation and maintenance as that of vapour absorption refrigeration system.
- Vapour compression refrigeration system applications are simple and compact but applications of vapour absorption refrigeration system are complex and space consuming.

3.5.2 Advantages

- Absence of moving parts, hence less noise.
- Exhaust system may be used as a source of heat energy.
- Load variation does not affect the performance of the system.
- Control is easy for absorption system.
- Cost of the system is less.

3.5.3 Disadvantages

- COP of the system is low.
- Leakages are a problem.
- This system occupies more space.
- Costly pump is required.

3.5.4 Difference between VARS and VCRS

The major difference between the two systems is the method of the suction and compression of the refrigerant in the refrigeration cycle. In the vapor compression system, the compressor sucks the refrigerant from evaporator and compresses it to the high pressure. The compressor also enables the flow of the refrigerant through the whole refrigeration cycle. In the vapor absorption cycle, the process of suction and compression are carried out by two different devices called as the absorber and the generator. Thus, the absorber and the generator replace the compressor in the vapor absorption cycle. The absorbent enables the flow of the refrigerant from the absorber to the generator by absorbing it.

Another major difference between the vapor compression and vapor absorption cycle is the method in which the energy input is given to the system. In the vapor compression system, the energy input is given in the form of the mechanical work from the electric motor run by the electricity. In the vapor absorption system, the energy input is given in the form of the heat. This heat can be from the excess steam from the process or the hot water. The heat can also be created by other sources like natural gas, kerosene, heater etc. though these sources are used only in the small systems.

Chapter 4

VAPOUR ABSORPTION REFRIGERATION SYSTEM DESIGN

4.1 Circuit design

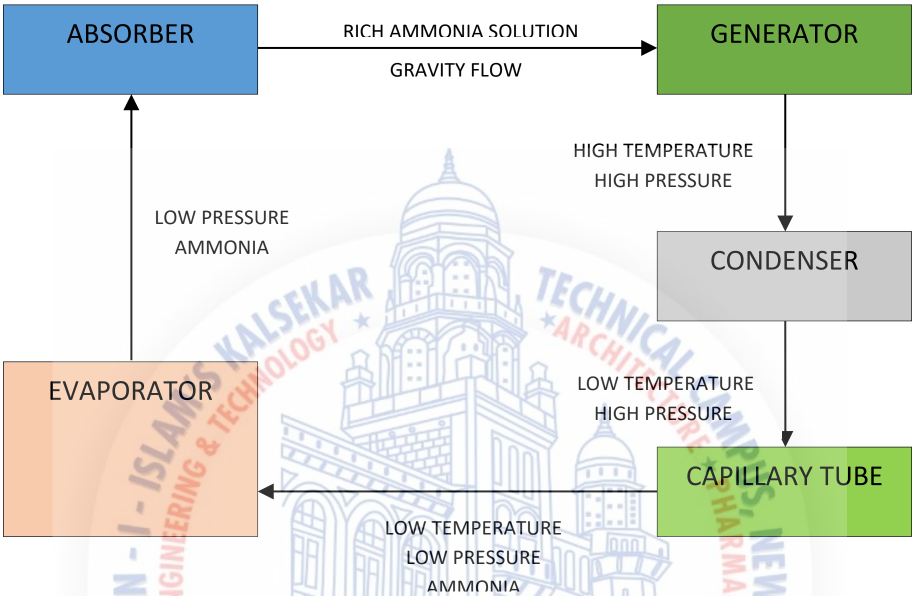

Fig 4.1: Vapour Absorption Refrigeration System circuit design

4.2 Structure design

A complete test rig of vapour absorption refrigeration system was constructed by assembling all the components. This assembly is used to conduct experiments using LiBr-Water as our refrigerant, Fig 4.2a and 4.2b shows the final assembly of the VARS test rig which was build.

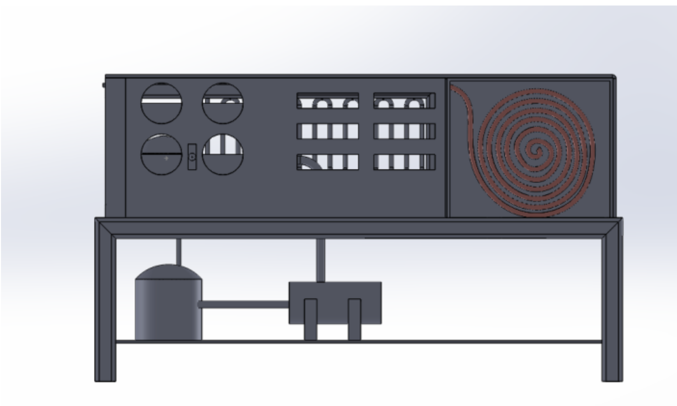

Fig 4.2a: Design of model in Solid works (Front view)

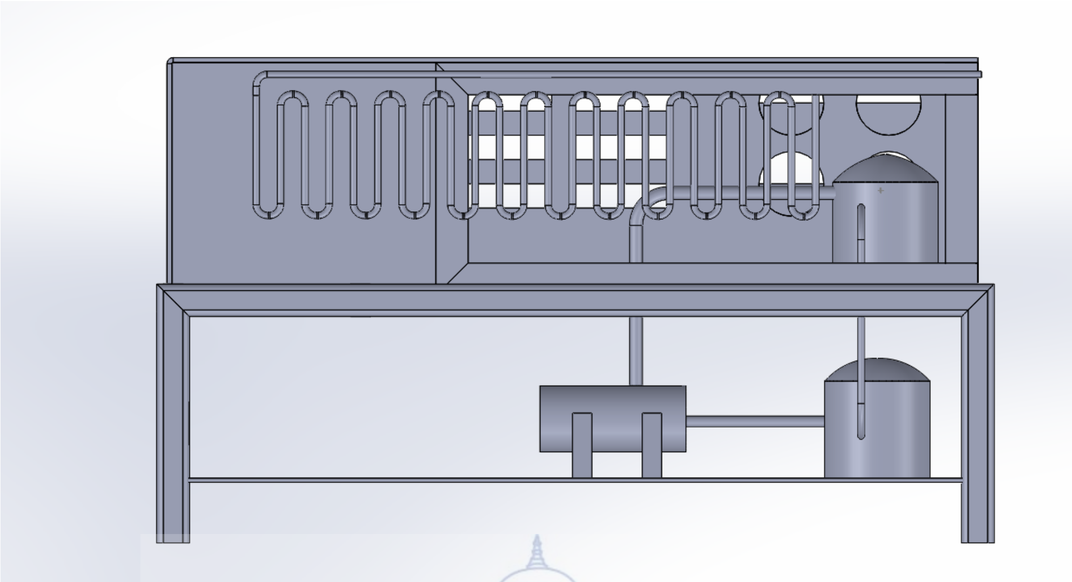

Fig 4.2b: Design of model in Solid works (Rear view)

4.3 Mechanism design

4.3.1 Generator

The purpose of the generator is to deliver the refrigerant vapour to the rest of the system. It accomplishes this by separating the water (refrigerant) from the lithium bromide and water solution. In the generator, a high-temperature energy source, typically steam or hot water, flows through tubes that are immersed in a dilute solution of refrigerant and absorbent. The solution absorbs heat from the warmer steam or water, causing the refrigerant to boil (vaporize) and separate from the absorbent solution. As the refrigerant is boiled away, the absorbent solution becomes more concentrated. The concentrated absorbent solution returns to the absorber and the refrigerant vapour migrates to the condenser**.** Material of generator box is stainless steel and the generator used is shown below in Fig 4.3.1.

Fig 4.3.1: Generator used in VARS

The Dimensions of the Generator used are,

Area of tube = $\pi DL = 2393\ mm^2$

Cross-sectional area of tube (A) = $\pi /4 \times d^{2} = 31.66\ cm^2$

Table 4.1 Generator Specifications

Parameter	Value
Tube dimension	Inside diameter *Di* =6.35mm
	Outside diameter *Do* = 6.8 mm
Height	130 mm
Length	180 mm
Width	150 mm
Generator pressure	7.35 kPa

4.3.2 Evaporator

The purpose of evaporator is to cool the circulating water. The evaporator contains a bundle of tubes that carry the system water to be cooled/chilled. High pressure liquid condensate (refrigerant) is throttled down to the evaporator pressure. At this low pressure, the refrigerant absorbs heat from the circulating water and evaporates. The refrigerant vapours thus formed tend to increase the pressure in the vessel. This will in turn increase the boiling temperature and the desired cooling effect will not be obtained. So, it is necessary to remove the refrigerant vapours from the vessel into the lower pressure absorber. Physically, the evaporator and absorber are contained inside the same shell, allowing refrigerant vapours generated in the evaporator to migrate continuously to the absorber as shown in Fig 4.3.2. We have used quarter inch thick copper tubes to make the evaporator.

Fig 4.3.2: Copper tube is used to make Evaporator for VARS

Following are the specifications of the evaporator used,

Length of evaporator tube(L) is 9 feet and number of turns (n) is 6

Diameter of evaporator tube (D) = 6.35 mm

The effective area of evaporator

$(A_e) = n \times \pi \times D \times L = 6 \times 3.14 \times 0.635 \times 30 = 359.08 cm^2 = 35908 mm^2$

where, n is number of coils and L is length of tube.

Evaporator Design Parameters:

Table 4.2 Evaporator Specifications

Parameter	Value
Tube dimension; Inside diameter	Di=3.175mm
Tube dimension; Outside diameter	Do=4.175mm
Height	210 mm
Diameter	190 mm
Area	182055 mm^2
Volume	5954100 mm^3

4.3.3 Condenser

The purpose of condenser is to condense the refrigerant vapours. Inside the condenser, cooling water flows through tubes and the hot refrigerant vapour fills the surrounding space. As heat transfers from the refrigerant vapour to the water, refrigerant condenses on the tube surfaces. The condensed liquid refrigerant collects in the bottom of the condenser before traveling to the expansion device. Condenser is made up of mild steel as shown in Fig: 4.3.3. There are lot of fins provided.

Fig 4.3.3: Condenser for VARS

The following are the specifications of the condenser used,

No. of tubes = 10

Radius of circular edges =10 mm

Length of each tube (L) =450 mm

Table 4.3 Condenser Specifications

Parameter	Value
Tube dimension; Inside diameter	D_i= 3.175 mm
Tube dimension; Outside diameter	D_o = 4.175 mm

4.3.4 Absorber

Inside the absorber, the refrigerant vapour is absorbed by the lithium bromide solution. As the refrigerant vapour is absorbed, it condenses from a vapour to a liquid, releasing the heat it acquired in the evaporator.

The absorption process creates a lower pressure within the absorber. This lower pressure, along with the absorbent's affinity for water, induces a continuous flow of refrigerant vapour from the evaporator. In addition, the absorption process condenses the refrigerant vapours and releases the heat removed from the evaporator by the refrigerant. As the concentrated solution absorbs more and more refrigerant; its absorption ability decreases. The weak absorbent solution is then pumped to the generator where heat is used to drive off the refrigerant. The hot refrigerant vapours created in the generator migrate to the condenser. The condenser turns the refrigerant vapours to a liquid state and picks up the heat of condensation, which it rejects to air. The liquid refrigerants return to the evaporator and completes the cycle. The material used for making absorber is iron, copper pipe is folded inside the absorber shell as shown in Fig 4.3.4.

Fig 4.3.4: Absorber for VARS

Table 4.4 Absorber Specifications

Parameters	Value
Tube dimension; Outside diameter	D_o = 6.8 mm
Length	170 mm
Height	180 mm
Width	130 mm
Volume	4000000 mm^3

4.3.5 Capillary tube:

From the condenser, the liquid refrigerant flows through an expansion device into the evaporator. The expansion device is used to maintain the pressure difference between the high-pressure (condenser) and low-pressure (evaporator) sides of the refrigeration system by creating a liquid seal that separates the high-pressure and low-pressure sides of the cycle. As the high-pressure liquid refrigerant flows through the expansion device, it causes a pressure drop that reduces the refrigerant pressure to that of the evaporator. This pressure reduction causes a small portion of the liquid refrigerant to boil off, cooling the remaining refrigerant to the desired evaporator temperature. The cooled mixture of liquid and vapour refrigerant then flows into the evaporator.

The material used for making capillary tube is copper. The length of capillary tube is 6m. And the diameter of Capillary tube is 0.3mm.

Fig 4.3.5: Capillary tubes

4.3.6 Connectors

Copper connectors are used to connect the capillary tube in between generator and absorber which helps in increasing the pressure and reducing temperature of refrigerant after it passes through the expansion valve. A connector is shown in Fig 4.3.6.

Fig 4.3.6: Connector for VARS

4.3.7 Pump

It is used to pump the solution of lithium bromide and water from absorber to the generator. It is driven by current supplied by the battery. Only one pump is used to pump our refrigerant into the generator from the absorber as shown in Fig 4.3.7.

Pressure head = 2m, Power = DC 12V

Fig 4.3.7: Pump

4.3.8 Digital Thermometer

A thermometer with digital display is used to measure temperature at various sections of the VARS cycle as shown in figure below. The Thermocouple used here is of a K-type thermocouple having a range of -10^{0}C to 80^{0}C.It works on two button batteries. A thermocouple used in our test rig is shown in Fig 5.11. We have used 7 thermocouples to measure temperatures for our test rig.

Temperature range = -10^{0}C to 80^{0}C

Fig 4.3.8 Digital Thermometer

4.3.9 Valves

Valves are used to control and regulate the flow throughout the VARS cycle. It is used to connect the various components through copper pipes. These valves are used as connections between the generator and absorber to which the pump is connected. The valves are mounted on a ¼ inch copper tube which is used to regulate the flow of refrigerant through the pipes. Valves like these are installed as an inlet and outlet to the absorber and the valves used are shown in Fig 5.12

Fig 4.3.9 Valves used in VARS

4.3.10 Heater

Heater of 1000W capacity is used to heat the refrigerant, the heater is kept adjacent to the generator which imparts heat to the generator, increasing temperature of refrigerant inside the generator. A dimmer stat is used to control the voltage output of the heater to control the temperature. The Fig 4.3.10a shows heater involved in our experiment and plate 4.3.10b shows the dimmer stat.

Fig 4.3.10a Heater

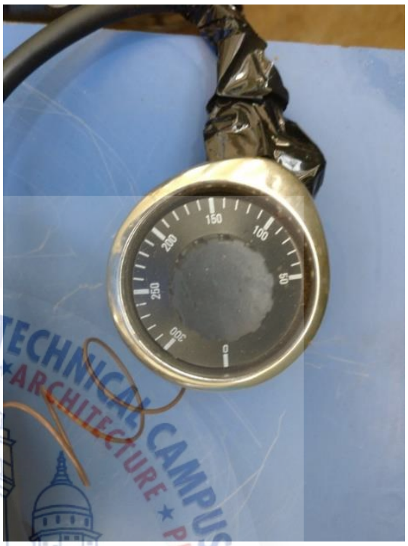

Fig 4.3.10b Dimmer Stat

4.3.11 Lithium Bromide (LiBr)

Lithium bromide (LiBr) is a chemical compound of Lithium and Bromine. It's extreme hygroscopic character makes LiBr useful as a desiccant in certain air conditioning systems. LiBr is prepared by treatment of lithium carbonate with hydrobromic acid. The salt forms several crystalline hydrates, unlike the other alkali metal bromides. The anhydrous salt forms cubic crystals similar to common salt (sodium chloride).

Lithium hydroxide and hydrobromic acid (aqueous solution of hydrogen bromide) will precipitate lithium bromide in the presence of water.

$$\mathbf{LiOH + HBr \rightarrow LiBr + H_2O}$$

5.11.1Physical and chemical properties of LiBr

MSDS Name: Lithium Bromide – 55% solution (Lithium – 99% & Water – 51-53%)
Physical State: Liquid
Color: Colourless to pale yellow
Odor: odourless
pH: Neutral
Vapor Pressure: 1.0 mm Hg @ 748C
Boiling Point: 225º F
Freezing/Melting Point: 45º F
Flash Point: Not applicable.
Explosion Limits, lower: Not available.
Explosion Limits, upper: Not available.
Decomposition Temperature: Not available.
Solubility in water: 145 % @ 4C
Specific Gravity/Density: 1.63
Molecular Formula: LiBr
Molecular Weight: 86.845

Precautions while using LiBr

Eyes: Wear safety glasses and chemical goggles if splashing is possible.

Skin: Wear appropriate protective gloves and clothing to prevent skin exposure.

Respirators: Wear a NIOSH/MSHA or European Standard EN 149 approved full-facepiece airline respirator in the positive pressure mode with emergency escape provisions.

4.4 Methodology

A review was made from the above-mentioned research papers and it is found out that construction of a LiBr-water vapour absorption test rig is viable option and is more efficient in terms of performance in comparison of ammonia. Based on this review a VARS test rig was constructed. The Refrigerant to be used has a concentration of 55% LiBr and 45% water. Using a refrigerant with higher concentration of LiBr in the solution will clog the tubing because of crystallization whereas increasing the concentration of water will raise the temperature of evaporation of the refrigerant in the generator. The tests were conducted on three separate days across three weeks.

Steps in Construction

1) Literature survey has been done and specifications of various components have been listed down.
2) Using the specifications of components, the test rig should be assembled.
3) Using refrigerant of concentration of 55% LiBr and 45% water, experimentation has to be carried out.
4) Experiment is to be conducted using LiBr-water solution as the refrigerant, three separate days for 70 minutes each and readings should be taken at an interval of 10 minutes.
5) Temperature v/s Time graph has to be plotted according to the readings.
6) Various COP's have been to be plotted against time.

4.5 Experimental Procedure

1) Measure 4.5 litres of Lithium Bromide-Water solution and fill it in the absorber via the inlet valve.
2) The inlet valve of absorber must be closed, and pump must be turned on.
3) A mass flow rate of 700 ml per min (0.01kg/s) must be set using valves provided.
4) The heater is turned on and the dimmer stat knob must be set to 120 on its dial.
5) The pump is turned on. The Refrigerant is pumped into the generator where heat is supplied. Temperature readings of the inlet to generator must be noted down.
6) As soon as the temperature readings of the condenser inlet rises above 45°C evaporator inlet condenser outlet temperatures must be noted down.
7) Simultaneously the pressure readings at the evaporator inlet must be noted and regulated as required.

8) The temperature of the solution entering back to the absorber must be checked and be maintained in a suitable range to get proper readings.
9) If the generator temperature increases beyond 80°C the dimmer stat must be regulated to arrive at required temp range.
10) All the thermocouple readings must be noted down at intervals of 10 minutes till the total time-period of the experiment is 70 minutes.
11) Finally, COP of the System must be calculated using formulas and find whether the machine is working in required COP range.
12) After the experiment the leftover solution is drained away from the absorber using the outlet valve.
13) The experiment is repeated as required.

Chapter 5

RESULTS & DISCUSSION

This chapter involves tabulation and calculation of the actual, theoretical, relative COP's. Results are compared based on the three trials taken for the repeatability test.

The test used a refrigerant mixture having a 55% LiBr-45% Water concentration and were conducted on three different days, across three weeks in the same month. The test duration was 70 minutes and the readings were taken at an interval of 10 minutes.

5.1 Experimental Observation

The Following Temperature readings were taken for 70 mins with a time interval of 10 mins on 4th April 2018 at 12:00 PM.

Table 5.1 Temperature readings for test conducted with time interval 10 mins on Day 1 of experimentation.

Time Min	Generator(°C)			Condenser Out(°C)	Evaporator(°C)			Actual COP	Theoretical COP	Relative COP
	Inlet	Outlet	Inside		Inlet	Outlet	Inside			
10	32.8	32.1	67.8	31.8	31.9	31.6	31.4	0.52	0.87	0.59
20	32.9	32.2	70.1	32.1	31.9	31.6	31.4	0.56	0.88	0.63
30	34.2	32.1	70.6	32.2	31.8	31.6	31.1	0.58	0.88	0.65
40	36.1	32.1	72.9	31.4	31.8	32.1	31.1	0.58	0.9	0.64
50	37.4	32	73.4	32.7	31.6	32.2	30.9	0.58	0.91	0.63
60	37.9	31.9	73.7	32.8	31.6	32.6	30.7	0.59	0.91	0.64
70	38.4	32.2	74.1	32.8	31.6	32.9	30.5	0.6	0.93	0.64

Calculations:

At Time 70 mins

1) Mass flow rate of weak solution, m_{ws} = 0.01 kg/s
2) Mass fraction of weak solution, ξ_{ws} = 0.55

   At pressure of 37mmHg and 74.1°C,

   Mass fraction of strong solution, ξ_{ws} =0.58
3) Circulation Ratio (λ)

$$\lambda = \xi_{ws} / \xi_{ss} - \xi_{ws} = \frac{0.55}{0.58-0.55} = 18.33$$

where,

ξ_{ws} = Mass fraction of weak solution

ξ_{ss} = Mass fraction of strong solution

4) Mass flowrate of Refrigerant, $m_{ws} = (1+\lambda) \times m$

$$0.01 = (1+18.33) \times m$$

$$m = 5.17 \times 10^{-4} \text{ kg/s}$$

5) Mass flow rate of strong solution, $m_{ss} = \lambda m$

$$=18.33 \times 5.17 \times 10^{-4}$$

$$=9.48 \times 10^{-3} \text{ kg/s}$$

6) Enthalpy of super heated vapour

   Temperature T_g = 74.1°C

   Enthalpy, $h_1 = 2501 + 1.88 (T_g - T_{ref})$ $T_{ref} = 0$

$$= 2501 + 1.88(74.1)$$

$$h_1 = 2640.30 \text{ KJ/kg}$$

7) Enthalpy of Liquid at condenser:

   Temperature T_c = 32.8°C

   Enthalpy, $h_3 = h_2 = 4.19 (T_c - T_{ref})$

$= 4.19\ (32.8)$

$h_2 = h_3 = 137.43$ KJ/kg

8) Enthalpy of vapour at evaporator:

Temperature $T_e = 1.3°C$

Enthalpy, $h_4 = 2501 + 1.88\ (T_e - T_{ref})$

$= 2501 + 1.88(1.3)$

$h_4 = 2503.44$ KJ/kg

9) Enthalpy of weak solution at absorber:

Temperature $T_a = 38.4°C$ at 55% Concentration Li-Br

Enthalpy, $h_5 = h_6 = -160$ KJ/kg (from h-c-p Chart)

10) Enthalpy of strong solution at generator:

At t = 74.1 at ξ=0.58

$h_7 = -100$ KJ/kg (from h-c-p Chart)

11) Heat Capacity of Evaporator, $Q_e = m(h_4 - h_3)$

$= 5.17 \times 10^{-4}\ (2503.44 - 137.43)$

$Q_e = 1.22$ KW

12) Heat Capacity of Generator, Q_g

$Q_g = mh_1 + m_{ss}h_7 - m_{ws}h_6$

$= 5.17 \times 10^{-4} \times 2640.30 + 9.48 \times 10^{-3}\ (-100) - 0.01(-160)$

Q_g = 2.01 KJ/kg

Coefficient of Performance (COP):

1) Actual Coefficient of Performance, $COP_a = \frac{Qe}{Qg}$

$$= \frac{1.22}{1.91}$$

$$COP_a = 0.60$$

2) Theoretical Coefficient of Performance, $COP_{th} = \left(\frac{Te}{Tc-Te}\right)\left(\frac{Tg-Ta}{Tg}\right)$

$$= \left(\frac{274.3}{305.93-274.43}\right)\left(\frac{347.23-311.53}{347.23}\right)$$

$$= COP_{th} = 0.93$$

3) Relative Coefficient of Performance, $COP_r = \frac{COP\ a}{COP\ th}$

$$= \frac{0.60}{0.93}$$

$$COP_r = 0.64$$

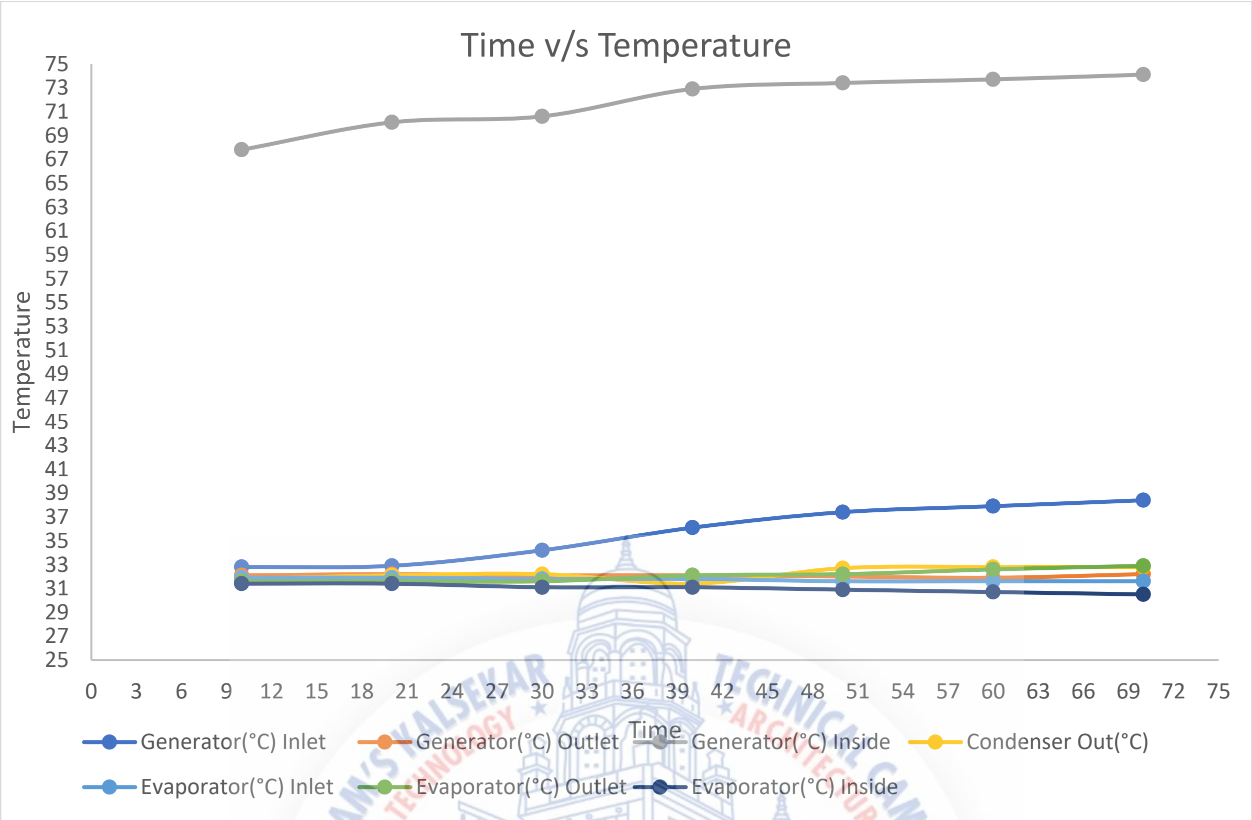

Figure 5.1 Time V/S Temperature

Figure 5.1 shows temperature readings of the system with respect to time, it is observed that as generator temperature increases, the condenser outlet, evaporator inlet and inside temperature decreases. The highest actual COP obtained for this day was 0.6 and for this reading the evaporator was cooled till 30.5°C.

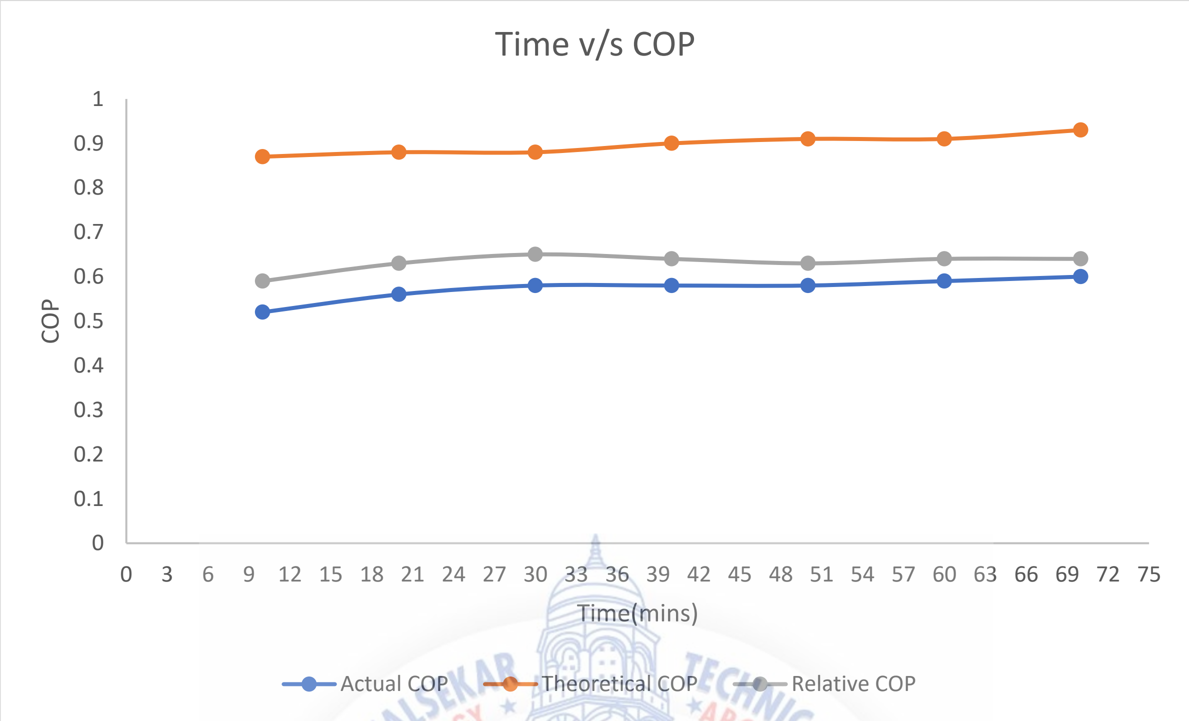

Figure 5.2 Time V/S COP

The fig 5.2 shows different COP's of the system with respect to time, it is observed that as time progresses the theoretical COP calculated is within the range of 0.92-0.98 whereas the actual and relative COP's had a steady increase.

The Following Temperature readings were taken for 70 mins with a time interval of 10 mins on 13th April 2018 at 12:00 PM.

Table 5.2 Temperature readings for test conducted with time interval 10 mins on 10th day of experimentation.

Time (mins)	Generator(°C)			Cond Out (°C)	Evaporator(°C)			Actual COP	Theoretical COP	Relative COP
	Inlet	Outlet	Inside		Inlet	Outlet	Inside			
10	31.3	32.7	65.2	30.1	31.9	31.3	32	0.53	0.92	0.58
20	31.5	33.4	67.7	30.9	31.9	31.5	31.8	0.56	0.95	0.59

30	31.6	33.9	69.6	31.2	31.8	31.7	31.7	0.57	0.95	0.59
40	31.8	34.5	71.2	32	31.7	32	31.4	0.57	0.96	0.60
50	32.4	36.2	73.4	32.7	31.5	32.1	31.4	0.58	0.95	0.61
60	32.7	40.2	75.6	33.4	31.3	32.2	31.1	0.59	0.97	0.61
70	32.9	40.8	76.5	34	31.4	32.4	30.9	0.60	0.98	0.62

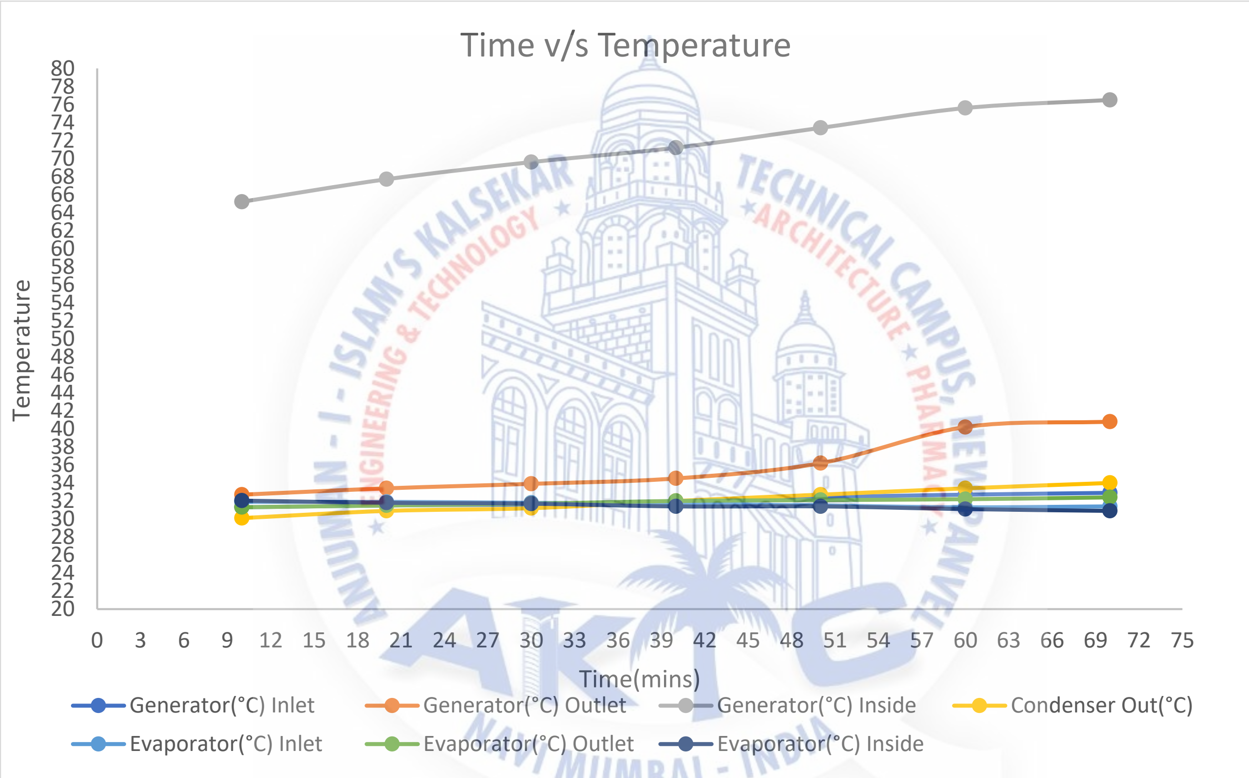

Figure 5.3 Time v/s Temperature

Figure 5.3 shows temperature readings of the system with respect to time. It is observed that as generator temperature increases the evaporator inlet and inside temperature decreases.

The maximum condenser temperature was 34°C at 70 minutes, and the temperature inside the evaporator was 30.9°C for the same time. The highest actual COP obtained for this day was 0.6

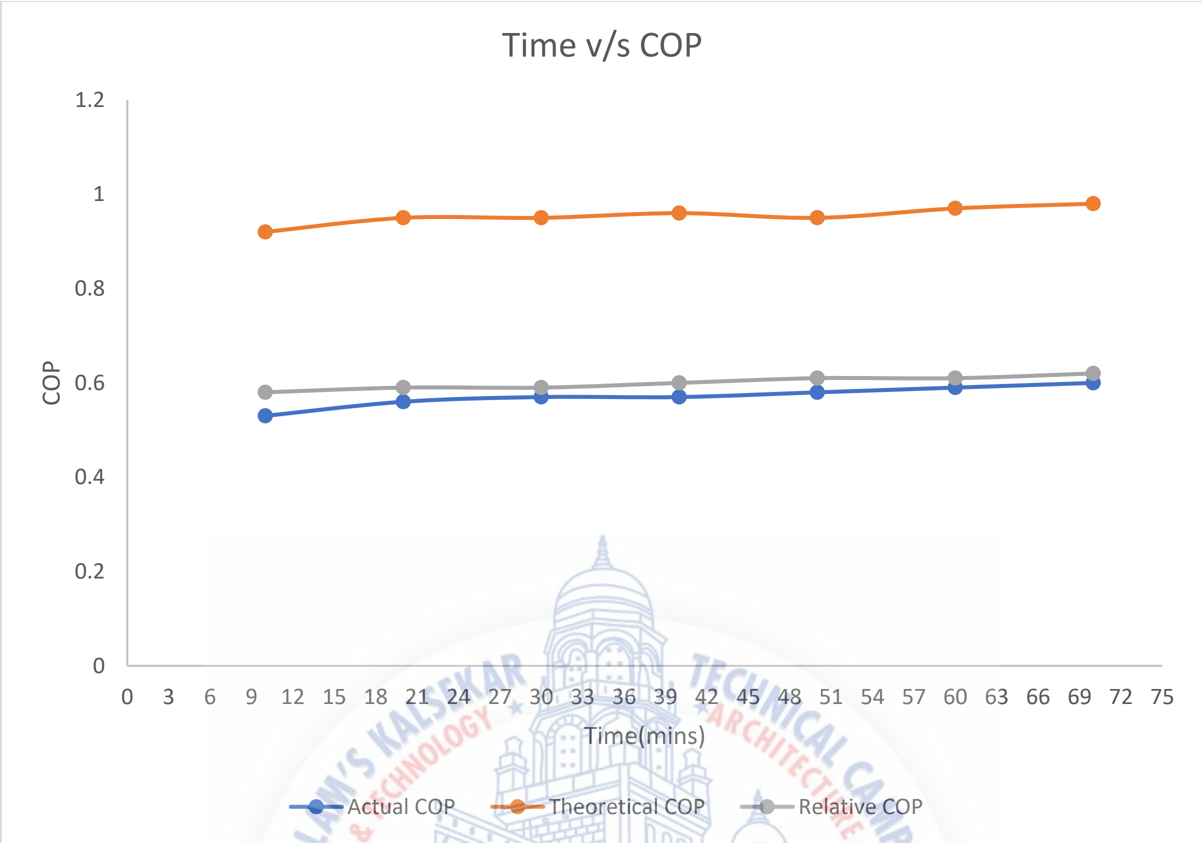

Figure 5.4 Time v/s COP

The figure 5.4 shows different COP's of the system with respect to time, it is observed that as time progresses the theoretical COP, actual COP and relative COP increased with increase in generator temperature and time.

The Following Temperature readings were taken for 70 mins with a time interval of 10 mins on 22nd April 2018 at 12:00 PM.

Table 5.3 Temperature readings for test conducted with time interval 10 mins on the 19th day of experimentation.

Time (mins)	Generator(°C)			Cond Out (°C)	Evaporator(°C)			Actual COP	Theoretical COP	Relative COP
	Inlet	Outlet	Inside		Inlet	Outlet	Inside			
10	31.6	33	65.4	31.1	30.8	31.2	31.6	0.50	0.88	0.57
20	31.8	34.5	67	31.3	30.9	31.2	31.4	0.52	0.91	0.58
30	32	36.1	67.2	31.3	30.8	31.4	31.4	0.53	0.92	0.58
40	32.4	35.3	70.2	31.2	30.6	31.4	30.9	0.55	0.94	0.59
50	32.4	35.6	72.5	31.1	30.5	31.7	30.5	0.57	0.97	0.59
60	32.6	37.6	74.3	31.3	30.3	31.9	30.3	0.58	0.97	0.60
70	32.7	40.2	74.8	31.2	30.2	32	30.2	0.61	0.99	0.62

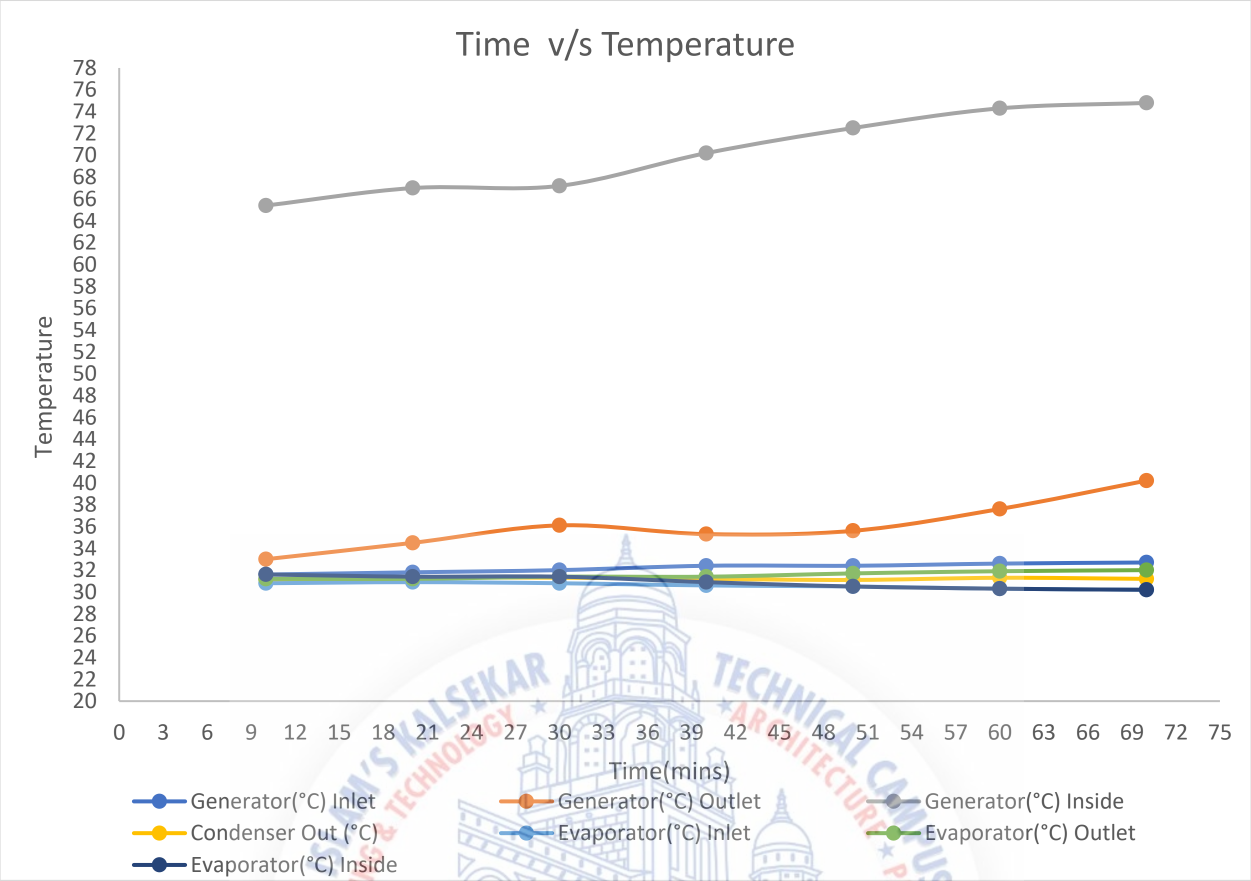

Figure 5.5 Time v/s Temperature

Figure 5.5 shows temperature readings of the system with respect to time, it is observed that as generator temperature increases the condenser outlet, evaporator inlet and inside temperature decreases. The highest actual COP obtained for this day was 0.61 and for this reading water was cooled till 30.2°C.

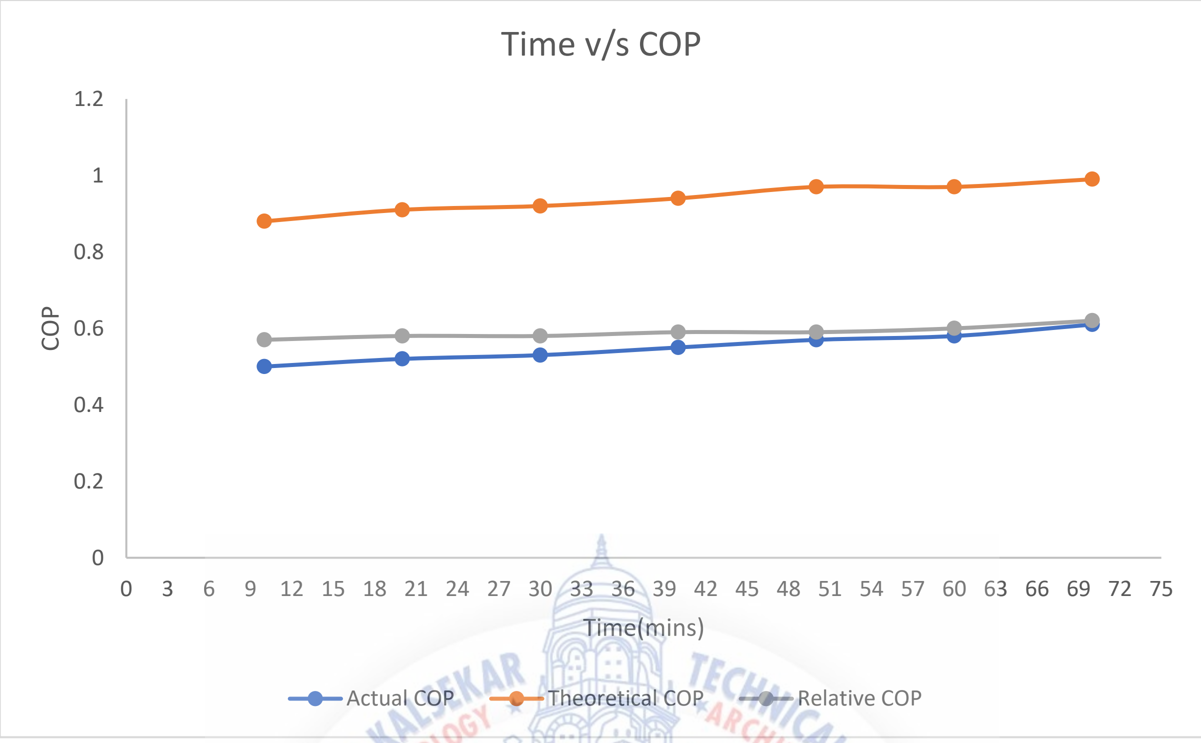

Figure 5.6 Time v/s COP

The fig 5.6 shows different COP's of the system with respect to time, COP of the system were similar to the COP calculated on the 2nd day of experimentation.

5.2 COMPARISON OF COP'S

Comparing the actual COP's of the experiments conducted for 3 different days

There is maximum deviation of actual COP at 30 minutes that is 8.6% and minimum deviation of actual COP at 70 minutes that is 1.6%.

Actual COP increases with increase in time, because as the temperature of the generator reaches closer to the evaporation temperature of the refrigerant mixture, the mixture evaporates faster in the generator, hence the circulation of refrigerant is quicker.

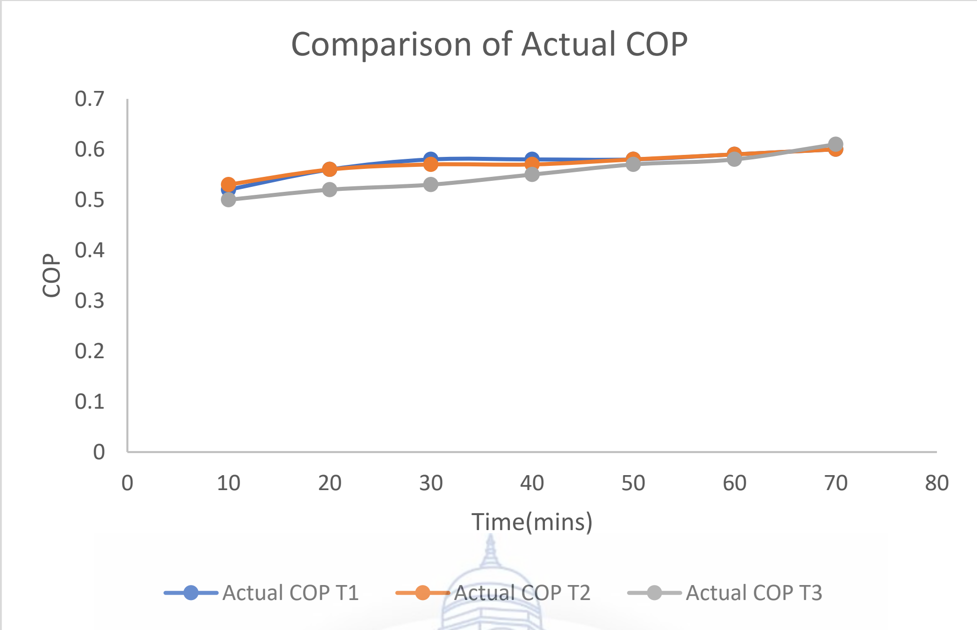

Figure 5.7 Actual COP Comparison for all 3 trials

Comparing the Theoretical COP's of the experiments conducted for 3 different days,

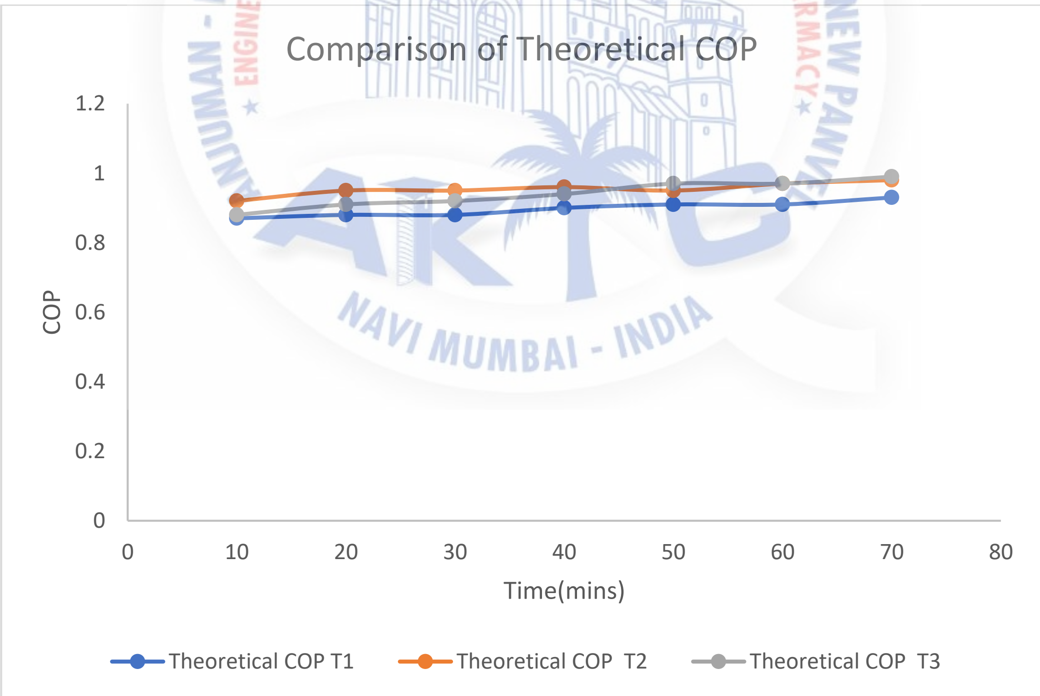

Figure 5.8 Theoretical COP Comparison for all 3 trials

The maximum deviation of theoretical COP at 30 minutes is 6% and minimum deviation of theoretical COP at 10 minutes is 2%. Since the test conditions were uncontrolled and the tests were conducted on different days, there will be changes in the theoretical COP for different trials.

Comparing the Relative COP's of the experiments conducted for 3 different days,

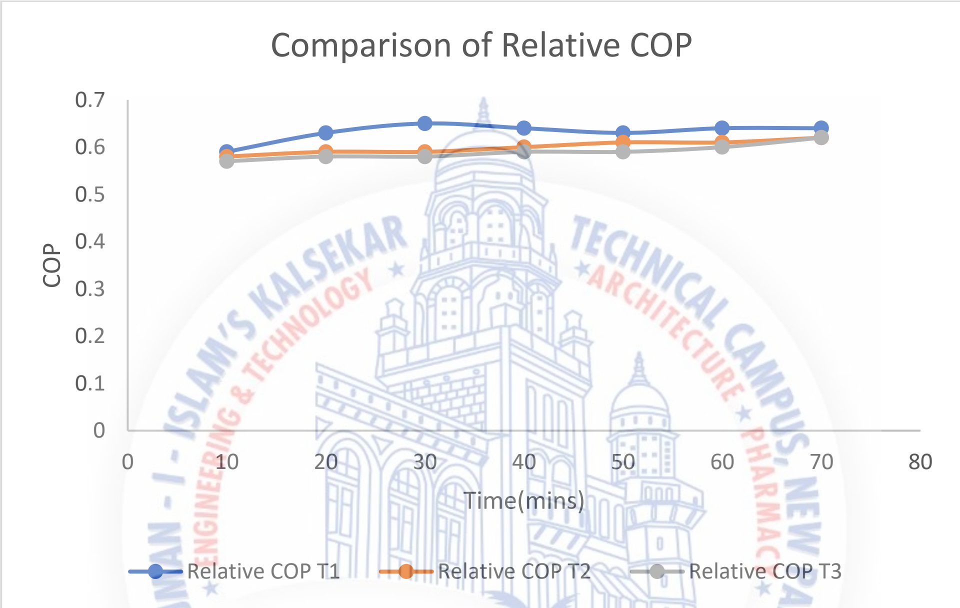

Figure 5.9 Relative COP Comparison for all 3 trials

The maximum deviation of relative COP is at 70 minutes i.e. 3.1% and minimum deviation of relative COP at 30 minutes i.e. 10.7%. Relative COP is the ratio of actual COP and theoretical COP. Actual COP increases with time and thus relative COP increases.

Chapter 6

CONCLUSION

After performing the experiments continuously after a certain interval on the vapour absorption refrigeration system, the following conclusions were made:

- Repeatability tests conducted on the test rig show that the test rig operates under VARS parameters and can be used for academic purposes to better understand the working of VARS on a large scale.
- The deviation for theoretical COP was found to be 6%-8% and that of actual COP to be 1%-9%. The deviation for relative COP was found to be around 3%-11%.
- The highest theoretical COP obtained was 0.99 at a generator temperature of 74.8ºC, the highest actual COP obtained was 0.61 for the same generator temperature and the highest relative COP obtained was 0.65.

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