

UTILIZATION OF SOLAR ENERGY IN ABSORPTION REFRIGERATION

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ABSTRACT

Solar energy can be utilized by, either, thermal conversion, or electrical conversion, of solar radiation. Utilization of solar energy by thermal conversion method, is of low cost, but it requires high density of solar radiation. Electrical conversion method, on the other hand, is expensive, but it does not need high density of solar radiation. One of the most important applications of thermal conversion of solar energy, is absorption refrigeration. As there are many factors affecting the process of solar refrigeration, a lot of research work must be carried out, before deciding an optimum design of solar refrigeration systems, which utilize solar energy at a low cost. The main objective of this research article is to design and construct an apparatus which can be used, as a test rig, by research students, to carry out experiments, regarding the performance of solar absorption refrigeration systems. The apparatus has been designed and constructed so as to be used indoors. One of the many different factors which affect the performance of solar absorption refrigeration systems, has been chosen, to test the apparatus, for functioning. This is the effect of condenser temperature, on the performance of solar absorption refrigeration systems. The apparatus has been tested for three different values of condenser temperature, and yielded very good results. The experimental work proves that, the coefficient of performance of a solar absorption refrigeration system, is high, at a low condenser temperature. At a condenser temperature of about 25°C, the actual coefficient of performance, obtained is 0.019, compared with a theoretical value of 0.062. And at a condenser temperature of about 15°C, the actual coefficient of performance is 0.026, compared with a theoretical value of 0.094.

Keywords: Design, solar heating, testing, intermittent, absorption, refrigeration

I. INTRODUCTION

Energy is one of the most serious problems facing developing countries. People in different societies, used to depend on petroleum, to provide them with energy. Petroleum is quite satisfactory for provision of energy, but, it is a limited source of energy, and there must be an end to this source. Regardless of this fact, the use of petroleum is associated with many problems, such as high running cost, and pollution of the environment, in addition, petroleum is not available for many people, in rural areas, due to problems of transportation and other factors. As a result, people in rural areas used to depend on coal and wood to provide them with energy. Using coal or wood for energy provision, has many disadvantages: It has bad effects regarding health

of people using it, in addition, it has a disastrous effect on environment. In such circumstances, renewable energy seems to be a good alternative.

One of the most important sources of renewable energy, is solar energy. Compared with other sources, solar energy is characterized by the fact that it is available, almost, everywhere, in addition, it is clean and does not have any bad effects on the environment. Solar energy can be utilized by one of the following two ways: 1. Conversion of solar radiation into electrical energy, using photovoltaic cells and 2. Conversion of solar radiation into direct heat energy, using solar collectors. Conversion of solar energy to electrical energy does not require high density of solar radiation. This is why photovoltaic cells, which convert solar energy to electrical energy, are widespread in Europe and other countries of similar climates, where solar radiation density is low. Conversion of solar energy to heat energy, on the other hand, requires high density of solar radiation, and it is therefore, the method which can be used in tropical climates, where solar radiation is very high. One of the most important factors which encourages use of thermal conversion of solar energy in tropical countries, is the cost. Solar collectors and associated components, can be manufactured, installed and operated at a very low cost, compared with photovoltaic cells. Due to intermittent nature of solar radiation a lot of research work should be carried out, to reach a suitable design which ensures optimum utilization of solar energy, at low cost. One of the most suitable applications of thermal conversion of solar energy, is absorption refrigeration. This is because, the power required to drive an absorption refrigeration system, is heat energy, which is directly available from a solar collector. A very interesting feature of solar refrigeration is that, solar radiation and cooling loads are approximately in the same phase, cooling loads are high when solar radiation density is high. This means that sufficient heat energy can be collected to meet power requirements of the cooling load. When solar radiation is low, on the other hand, cooling loads are low, and still sufficient heat energy, can be collected to drive the refrigeration system. Two main types of absorption refrigeration systems, are known to be used on the basis of the working fluid. These are: ammonia-water, and lithium bromide-water. In systems using ammonia-water solution, ammonia is the refrigerant and water is the absorbent. The properties of ammonia as a refrigerant, enables a very low temperature to be obtained in the cold space. In systems using lithium bromide-water solution, water is the refrigerant, and lithium bromide is the absorbent, hence, the cold space temperature, is limited to the temperature at which water transforms from liquid to ice. There are many factors affecting the process of solar absorption refrigeration.

The aim of this research includes two areas. The first one, is to write a computer program, which can be used to predict performance of absorption refrigeration systems, under varying conditions of operation. The second area, is to design and construct, a model of absorption refrigeration system, which can be used as an experimental rig to carry out experiments regarding the performance of solar absorption refrigeration systems. Ammonia-water system is used here since it gives lower temperature in the cold space, compared with lithium bromide water system. To simplify testing procedure, the experimental rig is to be an indoor model, which can be located inside

a laboratory, instead of being outdoors under solar radiation. Literature review of solar radiation, and refrigeration in general is covered in this research. Mathematical modeling of the system is also presented. System components are described and analyzed. Basic equations for each component are used to write the computer program, which shows effects of different parameters on the performance of the system. Design and construction of the system model, testing of the apparatus, results and discussion are presented in this research, which also includes comparison of experimental results with predictions. The objectives of the present study are: 1. To carry out a mathematical analysis of the intermittent absorption refrigeration system, and then write a computer simulation program, which can be utilized in predicting the performance of the system; 2. To design and construct an intermittent ammonia absorption refrigeration system, as an experimental unit; and 3. To carry out different experiments, to study the performance of the system, under different operating conditions, and then to compare the experimental results with those predicted by the simulation program.

II. LITERATURE REVIEW

1. Solar energy

Duffie & Beckman [1], defined the sun as a sphere of intensely hot gaseous matter with a diameter of 1.39×10^9 m. Its distance from the earth is about 1.5×10^{11} m. At the center of this sphere, the temperature is estimated at 8×10^6 to 40×10^6 K and the density about 10^5 kg/m³. The sun is considered as a continuous fusion reactor. The energy produced in the central zone, is transferred to the outer surface, and then radiated into space. At the outer surface, the temperature is estimated to be about 5000 K, and the density, about 3.5×10^{-7} kg/m³. The intensity of energy radiated from the sun, is considered to be constant [1]. The solar constant, G_{sc} is defined as the energy radiated from the sun per unit time, received on a unit area of a surface perpendicular to the direction of propagation of the radiation. The value of the solar constant adopted by the World Radiation Center, is 1367 W/m². The earth rotates about its axis, and at the same time rotates about the sun. This leads to variation in the distance between the earth and the sun, and, consequently, in the intensity of solar radiation outside the atmosphere (extraterrestrial radiation) [1]. When radiation passes through atmosphere, it is partly absorbed and scattered by the atmosphere. The radiation reaches the earth in two components: beam radiation and diffuse radiation. Beam radiation is the solar radiation received on the earth surface without being scattered by the atmosphere and diffuse radiation is the solar radiation received on the earth surface after it is scattered by the atmosphere. Solar energy can be converted to heat energy by using solar collectors, which collect heat, and transfer it to a given fluid. The heat is then used, in general, for heating, cooling, generating electricity or drying crops. Solar collectors are divided into two main categories: flat plate collectors and concentrating collectors. A flat-plate collector is, basically, an insulated box with a single or double glass cover. Flat plate collectors are used to provide heat energy at moderate temperatures, up to about 100° C above ambient temperature [1]. In a concentrating collector, an optical device is used to concentrate the incident radiation on to a small area. Concentrating

collectors are used to provide heat energy at a higher temperature compared with flat plate collectors. Two main types of concentrating collectors are used: parabolic dish collectors and parabolic trough collectors. In the parabolic dish collectors, dish shaped reflectors are used to concentrate solar radiation, on a receiver mounted above the dish at the focal point. Parabolic trough collectors, use parabolic reflectors in a trough configuration, to focus solar radiation on a tube running along the length of the trough, [2].

2. Refrigeration

Refrigeration is a process in which heat is transferred from a cold space, at low temperature, to a relatively hot space, at a higher temperature. As the natural flow of heat is always from a high temperature region to a lower temperature one, this means that, in the refrigeration process, an external energy is to be supplied, so as to force heat to flow in the opposite sense of its natural flow. The general applications of refrigeration are in food preservation and air conditioning. There are two common methods of refrigeration in general: vapor compression refrigeration, and absorption refrigeration [3].

Vapor Compression Cycle

Fig. 1 shows the main components of a vapor compression refrigeration cycle, and Fig. 2 shows the theoretical thermodynamic cycle of the process [3].

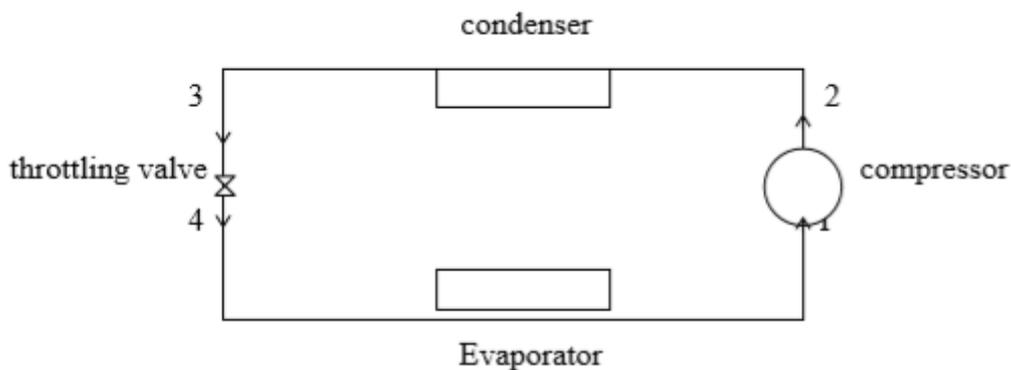


Fig. 1 Vapor Compression Refrigeration Cycle

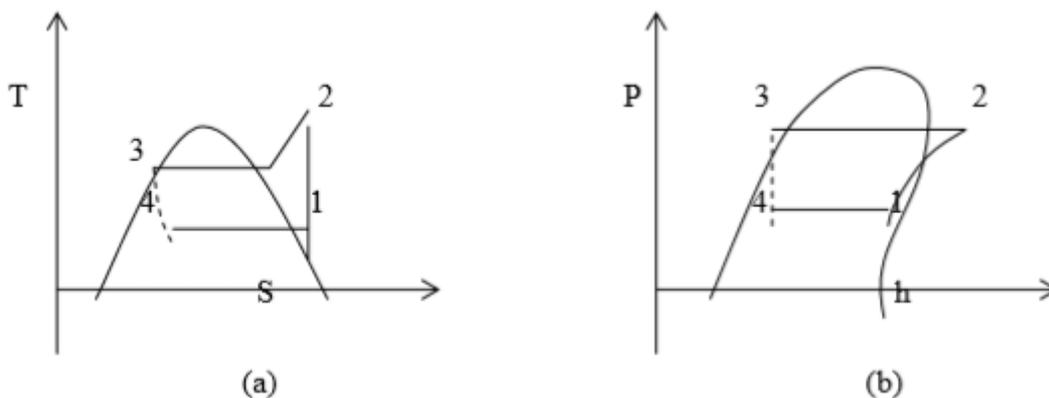


Fig. 2 Theoretical Cycle of a Vapor Compression Refrigeration

In the theoretical cycle, the refrigerant enters the compressor at state 1, as dry saturated vapor, where it is compressed isentropically to state 2, as superheated vapor. It then enters the condenser at a high pressure, where it gives up heat at constant pressure and leaves the condenser at state 3, as a saturated liquid. The refrigerant is then expanded through a throttling valve to state 4, where the pressure is lowered from the high condenser pressure to a low evaporator pressure. It then passes to the evaporator where it extracts heat from the cold space at the evaporator pressure and leaves at state 1 where it enters the compressor again and the process is repeated. The vapor compression cycle is characterized by the fact that, more energy is required to compress the vapor, [3]. The compressor work is given by the expression:

$$W_{12} = h_1 - h_2 \quad (1)$$

The quantity of heat removed from the cold space in the process 4-1, is the useful refrigerating effect, and is given by the following expression, as in reference [3]:

$$q_{41} = h_4 - h_1 \quad (2)$$

The capacity of a refrigerating system is measured in kW or Btu/hr. For large systems, the unit “ton of refrigeration”, is used which is equal to 3.5 kW or 12000 Btu/hr., as in references [4] and [5]. The performance of any refrigeration cycle is expressed in terms of the coefficient of performance (COP) which is defined by the ratio:

$$COP = \frac{\text{useful refrigeration effect}}{\text{net energy input}} \quad (3)$$

So, the COP of the theoretical cycle is given by:

$$COP = \frac{h_4 - h_1}{h_2 - h_1} \quad (4)$$

The compressor work and, hence, running cost of a refrigerating system, can be much reduced if the compressor is to compress a liquid, instead of vapor, [3]. This is the basis of an absorption refrigeration cycle.

Absorption Refrigeration

The vapor compression refrigeration system described above, is an efficient and practical method of refrigeration. However, the required energy input, is shaft work or power, which is high grade energy, and is expensive. The relatively large amount of work required is because of the compression of the vapor that undergoes a large decrease in volume [3]. The compression process can be replaced by a series of processes, where the refrigerant vapor is absorbed by a liquid, and then the liquid solution is pumped to a higher pressure. This reduces the shaft work required, but large quantities of heat must be transferred to the system, instead of mechanical energy, to make the change in the conditions, necessary to complete a refrigeration cycle [6].

Absorption systems are based on a combination of two substances, which have an unusual property. One substance will absorb the other without any chemical action taking place. It will absorb the other substance when cooled and release it when heated [6].

Fig. 3 shows the basic ammonia absorption refrigeration cycle, [3]. The condenser, evaporator and throttling valve are quite similar to those used in the compression cycle. The compressor of the vapor compression cycle, is replaced by the generator, absorber and pump. In Fig. 3 the generator contains a strong solution of ammonia in water, (aqua-ammonia solution). When heat is applied to the generator, ammonia vapor is released from the solution and passes to the condenser where it gives up heat and leaves the condenser as a liquid.

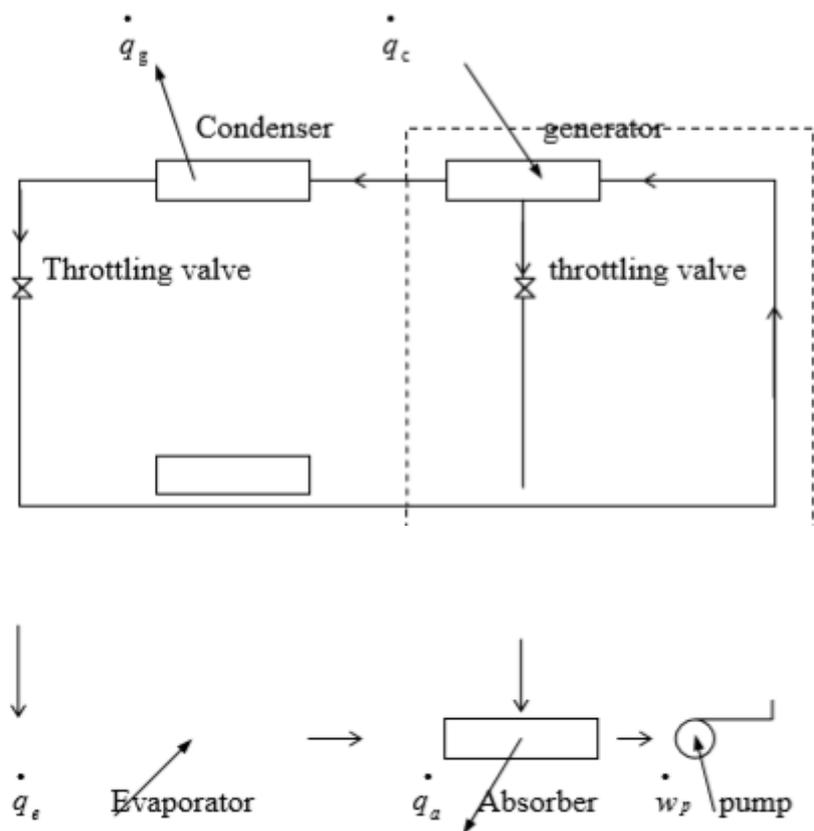


Fig. 3 Basic Absorption Cycle

It then enters the throttling valve, where its pressure is reduced to the evaporator pressure. The liquid refrigerant then flows to the evaporator, where it extracts heat and leaves the evaporator as a vapor. When ammonia vapor leaves the generator the remaining solution in the generator becomes weak, i.e. the concentration of ammonia is lowered. The weak solution from the generator returns to the absorber through a throttling valve, to reduce the pressure to the evaporator pressure. The ammonia vapor leaving the evaporator, enters the absorber where it is absorbed by the weak solution. After the absorption process, the weak solution, becomes strong and is then pumped at a high pressure to the generator where it is heated again and the cycle is repeated. The

absorption process in the absorber releases heat which must be continuously removed so as to continue the absorption process. There are several applications, which use absorption refrigeration systems, e.g. domestic refrigerators, cold stores, food preservation, recreational vehicles, air conditioning and industrial refrigeration. The required heat energy may be provided by using kerosene, natural gas, steam, electrical heating or solar energy [6]. The coefficient of performance of the absorption refrigeration cycle is generally low, however, waste heat such as that rejected from a power plant can be used to achieve better overall energy conservation [3].

The use of solar energy in absorption refrigeration, seems to be a good alternative irrespective of the value of coefficient of performance, this is, simply, because there is no running cost for any fuel to provide the input energy.

3. Solar Absorption Refrigeration

In solar absorption refrigeration systems, the heat input to the generator is obtained from solar energy by using solar collectors. Using solar energy in cooling is a very interesting application because, the available solar energy at any time is approximately proportional to the cooling loads required. When solar radiation is high, the need for cooling is increased and vice-versa, [1] and [7].

A schematic of a simple solar absorption refrigeration system is shown in Fig. 4. Water is heated in a flat plate collector and stored as hot water, in a storage tank. The hot water in the storage tank is then used to heat a binary mixture in the generator. Auxiliary heating system is provided as an alternative to solar heating. Due to heating, refrigerant is evaporated in the generator, and rises to the condenser where it is condensed to a liquid. It then enters the evaporator, where it absorbs heat from surroundings, and flows to the absorber. In the absorber, the refrigerant is absorbed by the absorbent, hence, the weak solution in the absorber, becomes strong. The strong solution is then pumped from the absorber to the generator and the cycle continues, [1].

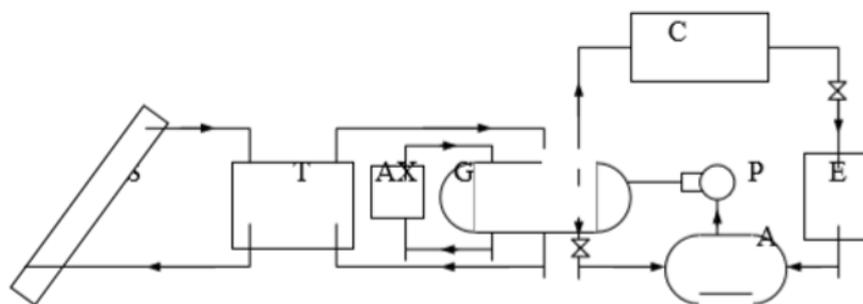


Fig. 4 Simple Solar Absorption Refrigeration System

S: solar collector, T: storage tank, Ax: auxiliary heating system, G: generator, C: condenser, E: evaporator, A: absorber, P: pump

Fig. 5 shows the pressure-temperature-concentration equilibrium diagram for an absorption cycle, using ammonia-water solution, [1]. The diagram shows the ideal

operation of the system. During the absorption process, ammonia vapor is absorbed by the weak solution, and hence the concentration of the solution increases. Continuous cooling of absorber is required during this process. When heat is applied to the generator, the pressure and temperature of the solution increase at constant concentration. When the saturation pressure is reached, ammonia starts to evaporate, the temperature of the solution continues to increase, the concentration decreases, and the pressure remains constant at the saturation pressure. Due to heat removal, the pressure and temperature decrease at constant concentration, until, ammonia vapor is returned back and be absorbed by the weak solution, in the absorber.

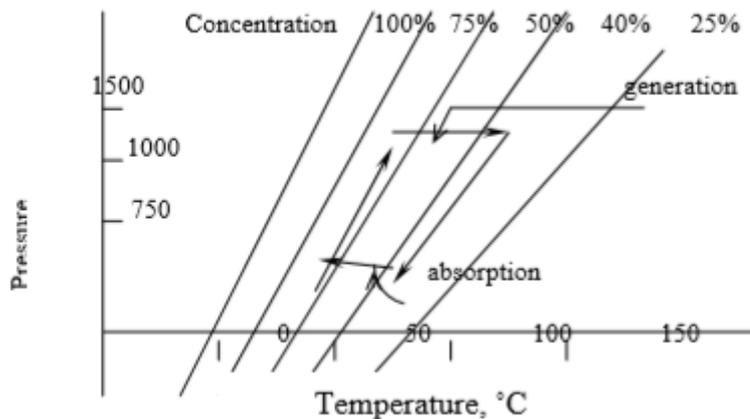


Fig. 5 Pressure, Temperature, Concentration Diagram for Aqua-Ammonia Solution with Water cooled Condenser and Absorber

Solar refrigeration systems can use continuous cycle or intermittent cycle. In continuous absorption cycles, heat energy is supplied to the generator from solar collector-storage tank-auxiliary heating system .

Continuous cycles work on the principles that, whenever cooling is required, then, heat energy is supplied to the system and at the same time, absorption process is taking place in the absorber. Therefore, generator and absorber of the continuous cycle must be different components. Sheridan [8] showed experimentally that lithium bromide-water solution can be used successfully in continuous cycles for solar air conditioning. Duffie and Sheridan, [9], studied analytically solar operation of LiBr – H₂O cooler and flat-plate collector combination. They showed that, among the different performance parameters, the generator design is the most critical one, because of the coupled performance of the collector and cooler.

In intermittent absorption cycles, the cycle starts with a regeneration process. When heat is added to the generator, refrigerant vapor is released from the absorbent, and is then condensed and stored as a liquid. The regeneration process continues for a period of about 4 to 6 hours during which, a certain quantity of refrigerant liquid, is collected and stored in a storage tank. The cooling occurs during the absorption process, which starts after the regeneration process has been completed. Fig. 6 shows a simple

intermittent absorption cycle in which the generator/absorber is a single vessel performing both functions and the condenser/evaporator is also a single vessel performing both functions, [1].

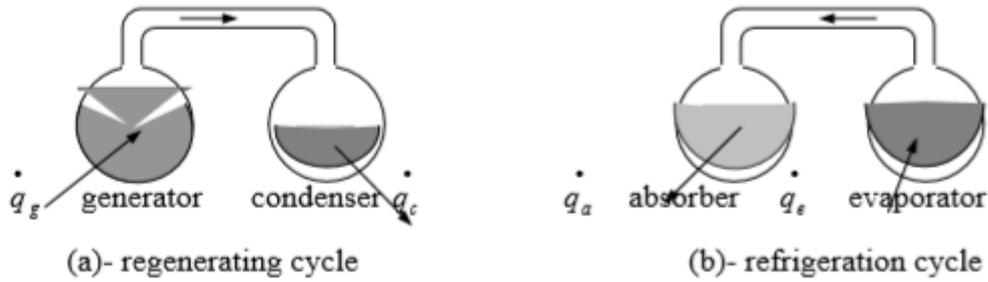


Fig. 6 Simple Intermittent Absorption Cycle

Chinnappa, [10] and [11], studied the performance of an absorption refrigeration system, operated by a flat plate collector. Swartman and Swami Nathan [12], studied, experimentally, the use of flat-plate collectors to drive an intermittent cycle using aqua-ammonia solution. In their experiments, the generator was an integral part of the collector. The aqua ammonia solution was circulated in the tubes of the collector. They used equal periods of 5 to 6 hours for regeneration and refrigeration cycles. The maximum generator temperature was 99°C , the cooling water temperature was about 30°C and the evaporator temperature was below 0°C . The overall coefficient of performance was found to be about 0.06. The effective cooling per unit area of collector surface per day was found to range from 50 to 85 kJ/m^2 for clear days.

4. Properties of Aqua-Ammonia Solution in Absorption Cycles

Aqua-ammonia solution is a binary homogeneous mixture, composed of pure ammonia and pure water. Binary mixtures, in general, behave in a different way, near saturation region, compared with pure substances. Faye, C. and Jerald, D. [3] explained this behavior by assuming an imaginary experiment. Assume that, the cylinder, shown in Fig. 7, contains aqua-ammonia solution in the liquid phase. This cylinder represent the generator in an absorption refrigeration system. The solution in the cylinder is subjected to a constant pressure, since the piston has a fixed mass and friction is assumed to be absent. Assume that the composition of the solution is indicated by the concentration of ammonia in water and is denoted by, x . Fig. 8 shows the temperature concentration diagram of the mixture. Assume that the initial concentration of ammonia in water is X_1 . State 1, on the t - x diagram is the initial state of the solution. When heat is applied to the cylinder, the temperature of the solution increases continuously, until point 2 is reached, where vapor starts to rise and collects under a constant pressure, which is applied by the piston, as shown in Fig. 7b. Point 2 lies on the boiling line. The boiling points of the mixture, lies between those of pure substances, t_w for water and t_a for ammonia, [13].

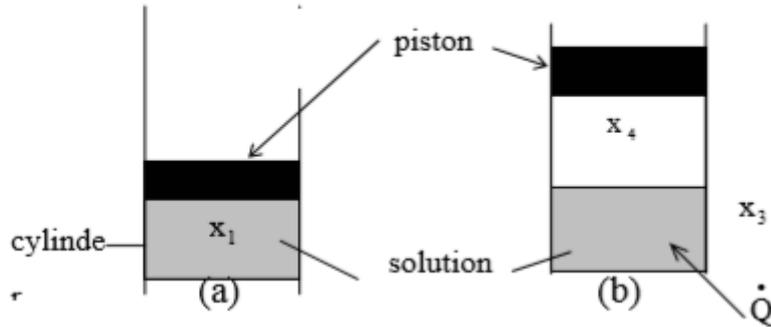


Fig. 7 Cylinder and Piston System

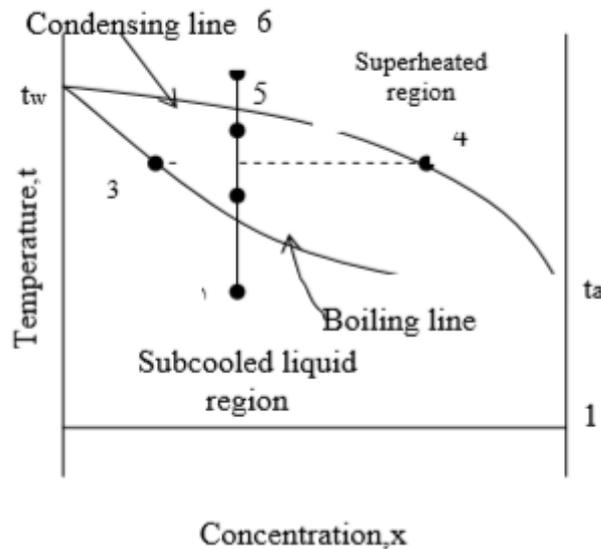


Fig. 8 Heating of Aqua-Ammonia Solution

If heating is continued, then the solution will be at some state such as state 3, whereas, the vapor, which is formed under the piston, will be at state 4, as shown in Fig. 8. The concentration of ammonia in vapor, first produced, is x_4 and not x_1 , i.e. the vapor is richer in ammonia, than the solution. Liquid at state 3 is in equilibrium with vapor at state 4, having the same pressure and temperature, and they can exist in equilibrium with each other, in any proportions, indefinitely as long as pressure and temperature, remain the same. If heating is continued further, then more vapor will be produced and eventually, all of the liquid will be converted to saturated vapor at state 5, with concentration, $x_5 = x_1$. Any further heating after point 5, will superheat the vapor to state 6. When this experiment is reversed, i.e., when a superheat vapor, at state 7, is cooled at constant pressure as shown in Fig. 9, then the vapor will start to condense at point 8, which lies on the condensing line.

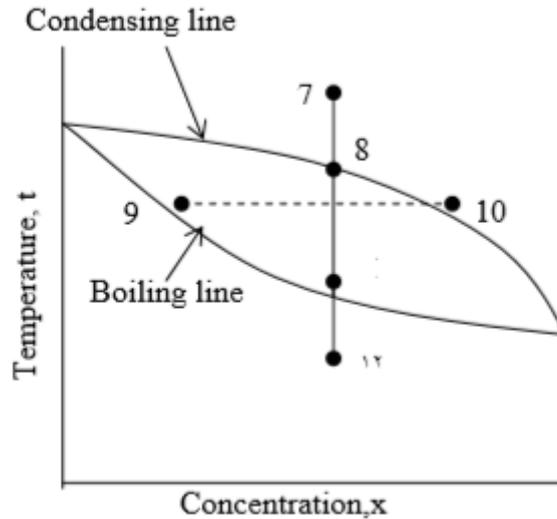


Fig. 9 Cooling of Aqua-Ammonia Vapor

If cooling is continued, then the condensed liquid, will be at some state such as state 9, whereas the remaining vapor will be at state 10. If cooling is continued further, then the whole vapor will be condensed to saturated liquid at state 11, with concentration $x_{11} = x_7$. Further cooling will sub cool the liquid to state 12.

Below the boiling line, subcooled liquid exists, and above condensing line, superheated vapor exists. Between the boiling line and condensing line, lies a two phase region, i.e., liquid and vapor exists simultaneously, both at the same pressure and temperature.

Boiling and condensing lines, shown in Figs. 8 and 9 are obtained by carrying out more experiments, at the same pressure, but different concentrations. If the pressure is now changed, and the experiment is carried out at different concentrations, then the boiling and condensing lines for new pressures will be shifted as shown in Fig. 10, as explained in references [3] and [13].

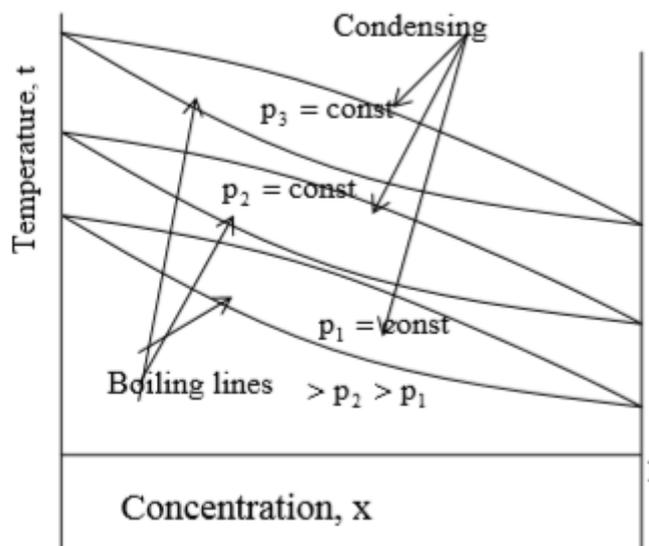


Fig. 10 Boiling and Condensing Lines at Different Pressures

Binary mixtures differ from pure substances in that, they do not have a single saturation temperature for each pressure, because, saturation temperatures depend on the concentration.

Enthalpy Concentration diagrams

Properties of binary mixtures, are usually represented in enthalpy concentration, (h-x), diagrams. Fig. 11, is a schematic h-x diagram for a binary mixture, [3].

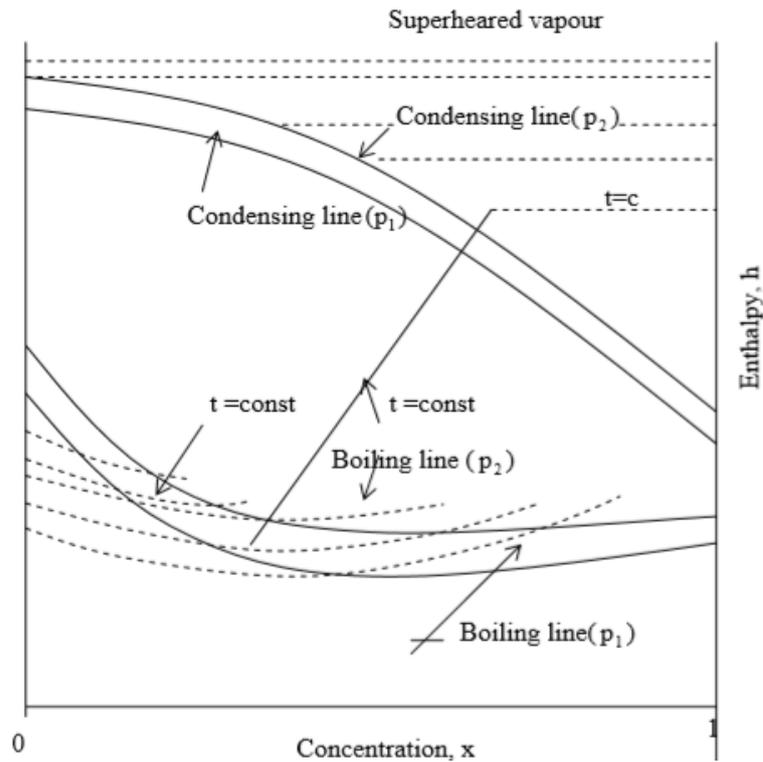


Fig. 11 Enthalpy Concentration Diagram

Isotherms are shown in the liquid and vapor regions but not in the saturation region. The enthalpy-concentration chart for aqua-ammonia solution, does not include isotherms in the vapor region. To locate lines of constant temperature in the saturation region, equilibrium construction lines are used, as described below, [3] and [13].

Adiabatic Mixing of Two Streams of Ammonia Water Mixture

Fig. 12 below shows a stream of ammonia water solution, at state 1, with concentration, x_1 and enthalpy h_1 flows at a rate of m_1 and mixes with another stream of the same solution, at state 2, with concentration, x_2 and enthalpy h_2 flows at a rate m_2 . The resulting mixture will be at state 3. To determine the properties of the new mixture, the following procedure is followed, [3]:

Fig. 13 below shows the graph of enthalpy, h against concentration, x.

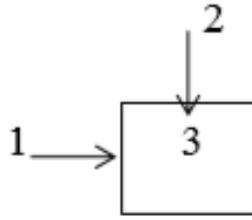


Fig. 12 Stream of Ammonia Water Solution

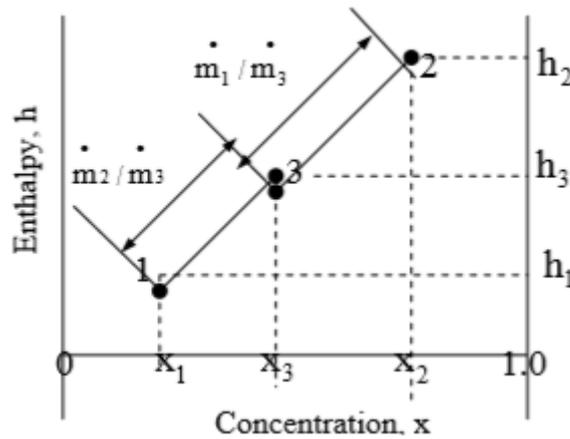


Fig. 13 Enthalpy, h against Concentration, x

The energy balance equation is given by the following formula:

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3 \quad (1)$$

The mass balance of ammonia is:

$$\dot{m}_1 x_1 + \dot{m}_2 x_2 = \dot{m}_3 x_3 \quad (2)$$

The overall mass balance is:

$$\dot{m}_1 + \dot{m}_2 = \dot{m}_3 \quad (3)$$

By substituting equation (3) in equation (1), and rearrange then,

$$\frac{\dot{m}_1}{\dot{m}_2} = \frac{h_2 - h_1}{h_3 - h_1} \quad (4)$$

Similarly, by substituting equation (3), in equation (2), and rearranging, then

$$\frac{\dot{m}_1}{\dot{m}_2} = \frac{x_2 - x_1}{x_3 - x_1} \quad (5)$$

From equations (4) and (5), then

$$\frac{\dot{m}_1}{\dot{m}_2} = \frac{h_2 - h_1}{h_3 - h_1} = \frac{x_2 - x_1}{x_3 - x_1} \quad (6)$$

To find the enthalpy of the resulting mixture, h_3 then, by substituting for \dot{m}_1

From equation (3), in equation (1), and rearranging, the following expression can be obtained:

$$h_3 = h_1 + \frac{\dot{m}_2}{\dot{m}_3} (h_2 - h_1) \quad (7)$$

Similarly, the concentration of the resulting mixture, is given by the following expression:

$$x_3 = x_1 + \frac{\dot{m}_2}{\dot{m}_3} (x_2 - x_1) \quad (8)$$

Mixing of Ammonia Vapor and Weak Aqua-Ammonia Solution with Heat Exchange

This is the process, which happens in the absorber of an absorption refrigeration system, [3]. In Fig. 14 below, saturated aqua-ammonia vapor, at state 2, mixes with weak saturated aqua-ammonia solution, at state 1. In this case the mass balance equations are the same as for adiabatic mixing, i.e.

$$\dot{m}_1 x_1 + \dot{m}_2 x_2 = \dot{m}_3 x_3 \quad (2)$$

$$\dot{m}_1 + \dot{m}_2 = \dot{m}_3 \quad (3)$$

But the energy balance equation, becomes:

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3 + \dot{Q} \quad (9)$$

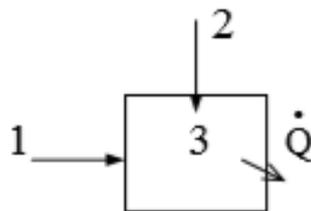


Fig. 14 Saturated Aqua-Ammonia Vapor mixes with Weak Saturated Aqua-Ammonia Solution

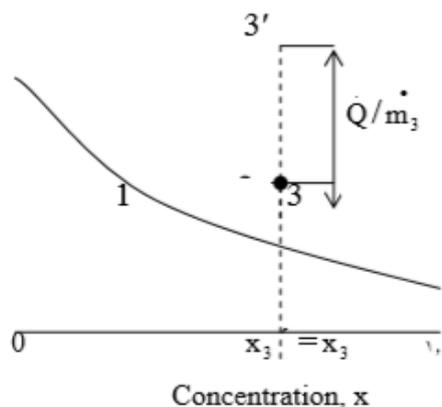


Fig. 15

Where, \dot{Q} is the quantity of heat removed from the absorber, during the mixing process. The concentration of the resulting mixture is given by the same expression as for adiabatic mixing, i.e.

$$x_3 = x_1 + \frac{m_2}{m_3} (x_2 - x_1) \quad (8)$$

To find the enthalpy of the resulting mixture, substitute for m_1 from equation (3), in equation (9) and rearrange, then:

$$h_3 = h_1 + \frac{m_2}{m_3} (h_2 - h_1) + \frac{\dot{Q}}{m_3} \quad (10)$$

In Fig. 15 point 3', represents a state that would result, if the mixing is adiabatic. Due to heat removal from the absorber in this case, then point 3 is located a distance $\frac{\dot{Q}}{m_3}$

Directly below point 3'.

III. MATHEMATICAL MODELING OF THE SYSTEM

1. Description of the System

The model under consideration is intended to be used as a test rig which can be used to carry out experiments regarding performance of solar absorption refrigeration systems which use ammonia-water ($\text{NH}_3 - \text{H}_2\text{O}$) solution. Fig. 1, shows a schematic diagram for the system components. The system consists of the following main components: solar collector, generator/absorber, condenser, receiver/ evaporator.

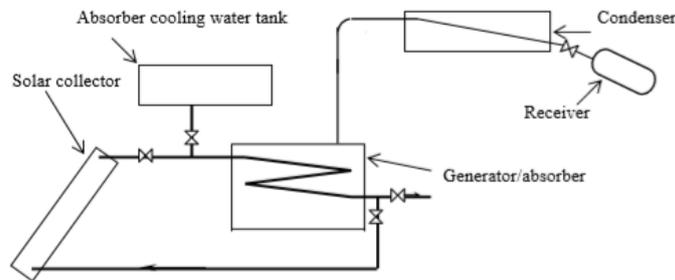


Fig. 1 Schematic Diagram for Intermittent Solar Absorption Refrigeration System

Solar Collector

This is a flat plate collector which is in a form of a box insulated from the bottom and the sides and covered with a glass cover, Fig. 2. In this research, the flat plate collector is to be directed towards the South. The collector consists of two horizontal tubes each of 1" inner diameter, one at the bottom, and the other one, at the top of the collector. These tubes, which form lower header and upper header respectively, are connected by a number of smaller tubes, of 1/2", inner diameter, and spaced at 100 mm intervals. The area of the flat-plate collector depends on the size of the refrigeration system. Water enters the collector, through the lower header, and it is naturally circulated, hot water

rises up and collected in the upper header. Hot water, then, flows outside the collector, from the upper header, through a ½" galvanized water tube, to the generator and then back to the collector, through the lower header.

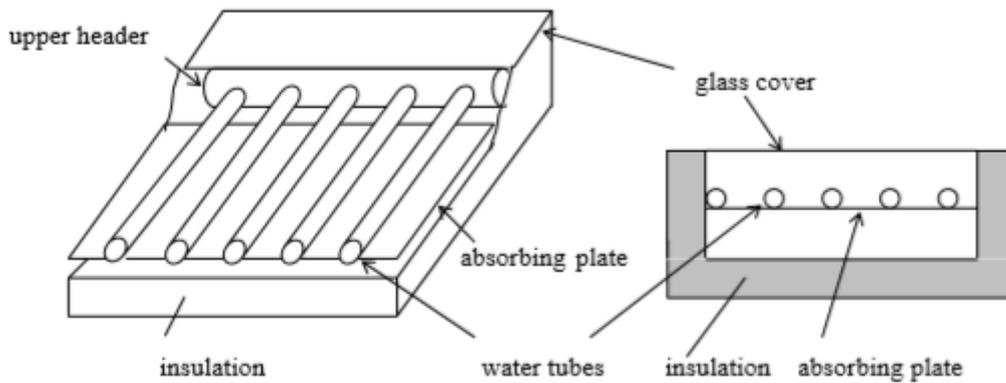


Fig. 2 Flat Plate Collector

Generator/Absorber

This is a single vessel, it is a shell type heat exchanger. It consists of a shell of 100 mm inner diameter, and three tubes each of 16 mm inner diameter, located inside the shell, Fig. 3. The shell is filled, up to about 60% - 80% of its volume, with a strong solution of aqua-ammonia of known concentration. The exact mass of the solution depends on the size of the model required. When working as a generator, steam and/or hot water is allowed to enter from the flat-plate collector through the tubes inside the shell and then back to the collector. The heat is transferred from the hot water, inside the tubes, to aqua-ammonia solution surrounding the tubes inside the shell, and hence the solution temperature and pressure increase. When the solution pressure reaches the saturation pressure, corresponding to the condenser temperature, ammonia starts to evaporate from the aqua-ammonia solution, and passes to the condenser coil, where it condenses to liquid ammonia, and flow, by gravity, to the receiver. The generation of ammonia vapor is expected to continue for a period of about 5 to 6 hours, during which the required quantity of ammonia liquid will be evaporated, condensed and stored in the receiver. During the absorption cycle, cold water is allowed to flow from the absorber cooling water tank, and enter to the tubes, which, are immersed in the aqua-ammonia solution inside the shell, and then back to the tank, or to the drain. The sudden cooling of the absorber reduces the temperature and, consequently, the pressure of the weak ammonia-water solution. The pressure in the absorber, therefore will be less than the pressure of pure ammonia in the receiver, hence, ammonia liquid, in the receiver, vaporizes, causes cooling effect there, and flows back, to be absorbed by the weak solution, in the absorber. The absorption process releases heat, so that continuous cooling of the absorber is required, throughout the absorption cycle.

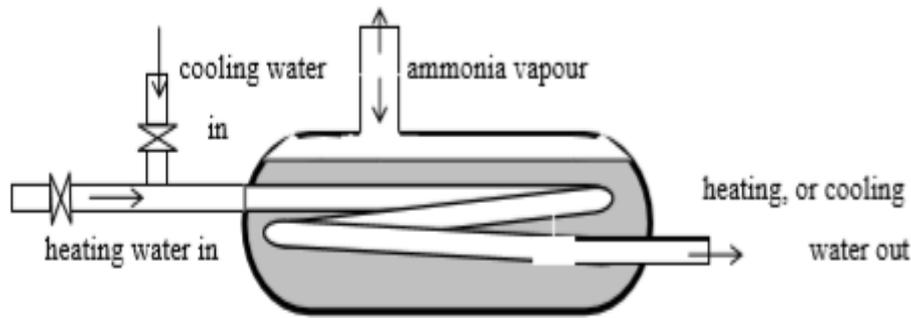


Fig. 3 Generator/Absorber

Condenser

During the regeneration cycle, evaporated ammonia passes through the condenser coil, which is made of a tube, of 16 mm inner diameter and 22 mm outer diameter, submerged in an insulated water tank, Fig. 4.

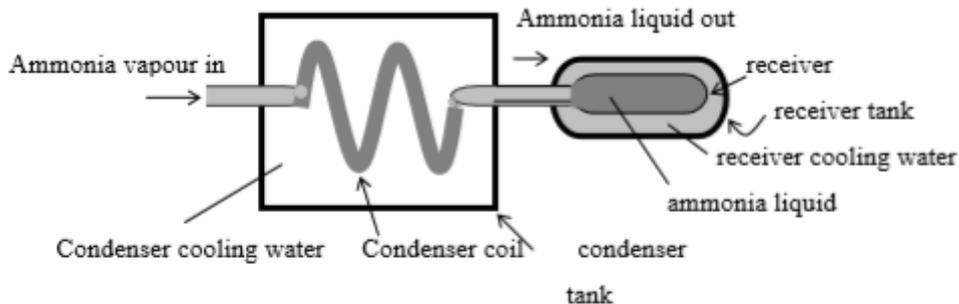


Fig. 4 Condenser and Receiver

When ammonia vapor passes through the condenser coil, heat is transferred, through the tube wall, to the cooling water, in the tank, and hence, ammonia vapor is condensed to ammonia liquid. The condenser coil is sloping down from the inlet joint towards the outlet joint, so that, after condensation, ammonia liquid flows by gravity towards the end of the condenser coil, and then to the receiver, to be stored there, as ammonia liquid.

Ammonia Receiver

This is a single vessel, which serves as a storage tank, to the condensed ammonia liquid. It is in the form of a tube of smaller diameter located inside and concentric with another tube of a relatively larger diameter. The space between the two tubes is filled with water, Fig 4. After condensation, ammonia liquid flows by gravity to the smaller diameter tube and remains there, until the absorption cycle starts. Due to the sudden cooling of the weak aqua-ammonia solution, in the absorber, at the beginning of the absorption cycle, the pressure in the absorber will be lowered, and hence ammonia liquid, which was stored at a relatively higher pressure in the receiver tank, starts to

evaporate, and flows back to be absorbed by the weak solution in the absorber. Due to vaporization of ammonia, heat is removed from the water surrounding the receiver. Hence cooling effect is produced in the evaporator, during the absorption cycle. The absorption cycle continues for about 18 to 19 hours after the regeneration cycle has been completed.

2. Analysis of the Flat Plate Collector

Solar Time

The intensity of solar radiation throughout the day depends on the time at which solar energy is required. Solar energy calculations must be based on solar time of the site under consideration. Solar time is different from the local clock time. It is given by the following expression [1]:

$$\text{solar time} = \text{standard time} + \{ 4(L_{st} - L_{loc}) + E \} / 60 \quad (1)$$

Where:

Standard time is the local clock time.

L_{st} = the standard meridian for the local time zone.

For the Sudan, $L_{st} = 315^\circ$

L_{loc} = the longitude of the location in question.

For Khartoum, $L_{loc} = 327.5^\circ$ west.

E = Equation of time in minutes and is given by:

$$E = 229.2(0.000075 + 0.001868\cos B - 0.032077\sin B - 0.014615\cos 2B - 0.04089\sin 2B) \quad (2)$$

Where, n = number of day of the year and is found from Table 1. And B is given in degrees by:

$$B = (n-1) \times 360/365 \quad (3)$$

Angle of Incidence

The angle of incidence, θ , is defined as the angle between the beam radiation on a surface and the normal to that surface and is given by the following relation, [1]:

$$\cos\theta = \sin\delta\sin\varphi\cos\beta - \sin\delta\cos\varphi\sin\beta\cos\gamma + \cos\alpha\cos\varphi\cos\beta\cos\omega + \cos\delta\sin\varphi\sin\beta\cos\gamma\cos\omega + \cos\delta\sin\beta\sin\gamma\sin\omega \quad (4)$$

Where:

β is the slope angle of the surface, $0^\circ < \beta < 180^\circ$.

φ is the latitude, the angular location, north or south of the equator, north positive,

$$-90^\circ < \varphi < 90^\circ.$$

γ is the surface azimuth angle, the deviation of the projection, on a horizontal plane, of the normal to the surface from the local meridian, with zero due south, east negative and west positive, $-180^\circ < \gamma < 180^\circ$.

δ is the declination, the angular position of the sun at solar noon, i.e. when the sun is on the local meridian, with respect to the plane of the equator, north positive, $-23.5^\circ < \delta < 23.5^\circ$, and is given by the equation:

$$\delta = 23.45 \sin \{360(284 + n)/365\} \quad (5)$$

ω is the hour angle, the angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at 15° per hour, morning negative, afternoon positive and is given by the equation:

$$\omega = 15(t - 12) \quad (6)$$

Where, t is the solar time.

The zenith angle of the sun, θ_z , is defined as the angle between the vertical, and the line to the sun, i.e. the angle of incidence of beam radiation on a horizontal surface and is given by the following relation:

$$\cos \theta_z = \cos \varphi \cos \delta \cos \omega + \sin \varphi \sin \delta \quad (7)$$

Extraterrestrial Radiation

Extraterrestrial radiation is the solar radiation outside the atmosphere. It depends on the position of the earth relative to the sun. Duffie and Beckman [1] presented the following relation for extraterrestrial radiation:

$$G_{on} = G_{sc} \{1 + 0.033 \cos (360n/365)\} \quad (8)$$

Where:

G_{on} is the extraterrestrial radiation, measured on a plane normal to the radiation on the n th day of the year.

G_{sc} is the solar constant.

The solar extraterrestrial radiation incident on a horizontal plane is given by:

$$G_o = G_{on} \cos \theta_z \quad (9)$$

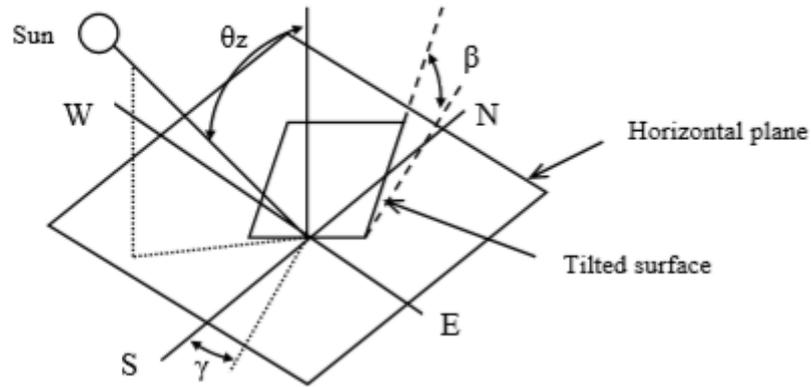


Fig. 5 Zenith Angle, Slope, and Surface Azimuth Angle For a Tilted Surface

Table 1 Recommended Average Days for Months and Values of n by Months

month	n for ith day of month	for the average day of the month		
		date	n day of year	δ , declination
January	i	17	17	-20.9
February	31+i	16	47	-13.0
March	59+i	16	75	-2.4
April	90+i	15	105	9.4
May	120+i	15	135	18.8
June	151+i	11	162	23.1
July	181+i	17	198	21.2
August	212+i	16	228	13.5
September	243+i	15	258	2.2

October	273+i	15	288	-9.6
November	304+i	14	318	-18.9
December	334+i	10	344	-23.0

Using equations (7) and (8), then, equation (9) can be written as:

$$G_o = G_{sc} \{1 + 0.033 \cos(360n/365)\} \times (\cos\phi \cos\delta \cos\omega + \sin\phi \sin\delta) \quad (10)$$

The solar radiation incident on a horizontal surface outside of the atmosphere, for an hour period, is found by integrating equation (10) for a period between hour angles

ω_1 And ω_2 which define an hour.

Where:

$\omega_2 > \omega_1$, thus:

$$I_o = (12 \times 3600 / \pi) G_{sc} \{1 + 0.033 \cos(360n/365)\} \times (\cos\phi \cos\delta (\sin\omega_2 - \sin\omega_1) + (\pi(\omega_2 - \omega_1) \sin\phi \sin\delta) / 180) \quad (11)$$

Clear Sky Radiation

When extraterrestrial radiation passes the atmosphere to the earth it is scattered and absorbed partially by the atmosphere. On the earth, the total radiation on a horizontal surface, I , consists of two components: beam radiation, I_b and diffuse radiation, I_d . i.e.

$$I = I_b + I_d \quad (12)$$

Hottel has presented a method for estimating the beam radiation transmitted through clear atmospheres. For an hour period, the method suggests the following relation, [14]:

$$I_b = \tau_b \times I_o \quad (13)$$

Where, τ_b is the atmospheric transmittance for beam radiation, and is given by the following equation:

$$\tau_b = a_o + a_1 e^{(-k / \cos\theta_z)} \quad (14)$$

a_o , a_1 and k are constants. For tropical climates, standard atmosphere, these constants are given by the following expressions:

$$\begin{aligned} a_o &= 0.95\{0.4237 - 0.00821(6 - A)^2\} \\ a_1 &= 0.98\{0.5055 - 0.00595(6.5 - A)^2\} \\ k &= 1.02\{0.2711 - 0.01858(2.5 - A)^2\} \end{aligned} \quad (15)$$

Where A is the altitude in kilometers of the given site.

The diffuse component on a horizontal surface is given by:

$$I_d = \tau_d \times I_o \quad (16)$$

Where τ_d is the ratio of diffuse radiation to the extraterrestrial radiation on a horizontal plane and is given by the following empirical relation which was developed by Liu and Jordan, [15]:

$$\tau_d = 0.271 - 0.294 \tau_b \quad (17)$$

The total radiation for an hour, incident on a flat-plate collector, inclined at slope angle β , is considered to include three components:

1. The beam component given by $I_b R_b$, where R_b is the geometric factor, which is defined as the ratio of beam radiation on the titled surface to that on a horizontal surface, i.e.

$$R_b = G_{b,t}/G_b = G_{b,n} \cos \theta / G_{b,n} \cos \theta_z = \cos \theta / \cos \theta_z \quad (18)$$

2. The diffuse component is given by:

$$I_d ((1 + \cos \beta)) / 2$$

3. Radiation diffusely reflected from the ground is given by:

$$I \rho_g ((1 - \cos \beta)) / 2$$

Where, ρ_g is the ground reflectance.

Therefore, the total solar radiation, for an hour, incident on a tilted surface, is given by:

$$I_t = I_b R_b + I_d \left\{ \frac{(1 + \cos \beta)}{2} \right\} + I \rho_g \left\{ \frac{(1 - \cos \beta)}{2} \right\} \quad (19)$$

Transmission of Radiation through Collector Cover

The material used for a collector cover must be transparent, so that, incident radiation can pass through it. The material used here is the glass. Not all of the incident radiation on the collector cover is transmitted, there are several losses, so that only part of the incident radiation on the collector can pass through collector cover and be absorbed by absorbing plate inside the collector. There are two kinds of losses; these are reflection and absorption of solar radiation by collector cover. Duffie and Beckman [1] have presented the following relation for calculation of the transmittance, τ , of a solar collector cover :

$$\tau = \tau_a \tau_r \quad (20)$$

In this equation, τ_a is the transmittance when only absorption losses have been considered and τ_r is the transmittance when only reflection losses have been considered. τ_a And τ_r are given by the following expressions:

$$\tau_a = e^{\frac{-KL}{\cos \theta_z}} \quad (21)$$

$$\tau_r = \frac{1}{2} \left\{ \frac{1-r_{pp}}{1+(2N-1)r_{pp}} + \frac{1-r_{pr}}{1+(2N-1)r_{pr}} \right\} \quad (22)$$

Where:

K is the extinction coefficient of the glass.

L is the thickness of the glass.

N is the number of covers.

r_{pp} and r_{pr} Are the perpendicular and parallel components of non-polarized radiation, respectively, and are given by the expressions:

$$r_{pp} = \sin^2(\theta_2 - \theta_1)/\sin^2(\theta_2 + \theta_1) \quad (23)$$

$$r_{pr} = \tan^2(\theta_2 - \theta_1)/\tan^2(\theta_2 + \theta_1) \quad (24)$$

Where θ_1 , is the angle of incidence of the radiation on the collector, and θ_2 , is the angle of refraction of the incident radiation, in the glass. θ_2 , is given by the relation:

$$\theta_2 = \sin^{-1}(\sin\theta_1/n) \quad (25)$$

Where n is the refractive index of the glass.

The above equations apply only to the beam component of solar radiation. In addition to beam radiation, the total radiation incident on a flat-plate collector also consists of diffuse radiation from the sky and radiation reflected from the ground. Brandemuehl and Beckman, [16], showed that the transmittance of the collector cover to diffuse and ground reflected radiation can be found from the same equations as the beam component, provided that, effective incidence angles are used for diffuse radiation and ground reflected radiation. These are given, respectively, by the following expressions:

$$\theta_{ed} = 59.7 - 0.1388\beta + 0.001497\beta^2 \quad (26)$$

$$\theta_{eg} = 90 - 0.5788\beta + 0.002693\beta^2 \quad (27)$$

Absorbed Radiation by the Absorbing Plate

If it is assumed that, the incident radiation on a collector has a magnitude of unity, then the radiation absorbed by the absorbing plate is given by the product $(\tau\alpha)$ where α is the absorptance of the absorbing plate. However only part of radiation transmitted through the glass cover and incident on the absorbing plate, is absorbed by the plate, and part of it, is reflected back to the glass cover. Some of this reflected radiation to the cover, in turn, is reflected back to the plate, to be absorbed partially by the plate and the rest of it is reflected again to the glass cover and so on, as shown in Fig. 6.

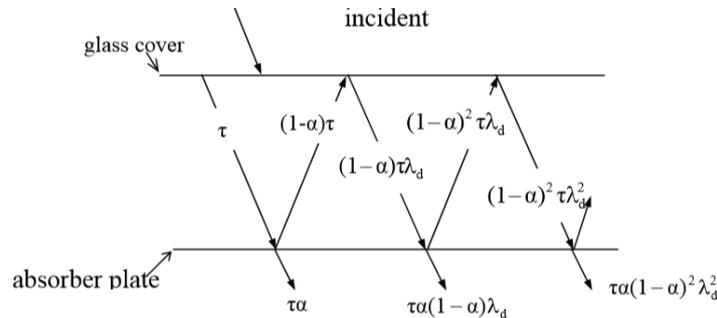


Fig. 6 Absorption of solar Radiation

Duffie & Beckman [1] stated that, the total radiation absorbed by the absorbing plate of the collector is given approximately by the expression:

$$(\tau\alpha) = 1.01\tau\alpha \quad (28)$$

Using equation (28) for beam, diffuse and ground reflected radiation, the corresponding transmittance – absorptance product ($\tau\alpha$) can be found, i.e.

$$(\tau\alpha)_b = 1.01 \tau_{cb} \alpha_{pb} \quad (29)$$

$$(\tau\alpha)_d = 1.01 \tau_{cd} \alpha_{pd} \quad (30)$$

$$(\tau\alpha)_g = 1.01 \tau_{cg} \alpha_{pg} \quad (31)$$

Subscripts c and p refer to cover and absorber plate and subscripts b, d and g, refer to beam, diffuse and ground reflected radiation respectively. The absorptance of the absorber plate is given by:

$$\alpha = \alpha_n \{1 + 2.0345 \times 10^{-3} \theta - 1.99 \times 10^{-4} \theta^2 + 5.324 \times 10^{-6} \theta^3 - 4.799 \times 10^{-8}\} \quad (32)$$

Where α_n , is the absorptance at normal incidence.

Note that the angle of incidence θ , is used to calculate the cover transmittance, τ_{cb} , and the plate absorptance, α_{pb} , for the beam radiation, as given by equations (20) and (32) respectively, whereas, effective incidence angles for diffuse and ground reflected radiation, as given, respectively, by equations (26) and (27), are used to calculate the corresponding cover transmittance, and plate absorptance. Equation (19) gives the total radiation incident on a titled collector, which consists of the three components: beam radiation, diffuse radiation and ground–reflected radiation. By multiplying each term of this equation,

By appropriate transmittance–absorptance product then the total radiation absorbed by the absorber plate, S, can be found, [1], i.e.

$$S = I_b R_b (\tau\alpha)_b + I_d (\tau\alpha)_d (1 + \cos\beta)/2 + \rho_g + (I_b + I_d) (\tau\alpha)_g (1 - \cos\beta)/2 \quad (33)$$

Useful Energy Gain of a Collector

Equation (33) gives the energy absorbed by a collector per unit area. Not all of this absorbed energy is useful, there are thermal losses to the surroundings. These losses which are due to conduction, convection and radiation can be represented as the product of an overall heat loss coefficient, U_L , times the difference between the mean absorber plate temperature T_{pm} and the ambient temperature T_a . So, the useful energy gain of a collector per unit area is given by:

$$Q_u = \{S - U_L (T_{pm} - T_a)\} \quad (34)$$

In this equation S is the average energy rate over one hour period with units of $J/m^2 \text{ hr}$. The usual units of U_L in SI units are $W/m^2 K$ or $J/sm^2 K$. So the thermal loss term in

the above equation, $U_L(T_{pm} - T_a)$, must be multiplied by 3600 s/hr. to obtain the useful energy gain in J/hr., [1], i.e.,

$$Q_u = \{S - 3600 U_L(T_{pm} - T_a)\} \quad (35)$$

Where S is the absorbed energy per unit area for an hour in Joules,(J), U_L is the overall heat loss coefficient in $K W/m^2$, T_a is the ambient temperature, and T_{pm} is the average absorber plate temperature, in K.

Collector Overall Heat Loss Coefficient, U_L

The overall heat loss coefficient consists of three components: top losses, bottom losses and edge losses. The energy loss through the top is the result of convection and radiation between parallel plates and is given by the following empirical Equation, [1] and [17]:

$$U_t = \left\{ \frac{N}{\frac{C}{T_{pm}} \{ [T_{pm} - T_a] / (N + f) \}^e + \frac{1}{h_w}} \right\}^{-1} + \frac{\sigma(T_{pm} + T_a)(T_{pm}^2 + T_a^2)}{(\varepsilon_p + 0.00591N h_w)^{-1} + \frac{2N + f - 1 + 0.133\varepsilon_p}{\varepsilon_g} - N} \quad (36)$$

Where:

N = Number of glass covers.

$$f = (1 + 0.089h_w - 0.1166h_w\varepsilon_p)(1 + 0.07866N)$$

$$C = 520(1 - 0.000051\beta^2) \quad \text{For } 0^\circ < \beta < 70^\circ. \text{ For } 70^\circ < \beta < 90^\circ, \text{ use } \beta = 70^\circ$$

$$e = 0.43(1 - 100/T_{pm})$$

β = slope angle of the collector (in degrees)

ε_g = emittance of glass

ε_p = emittance of absorber plate

T_a = ambient temperature (K)

T_{pm} = mean plate temperature (K)

h_w = Wind heat transfer coefficient (W/m^2K)

σ = Stefan – Boltzman constant (W/m^2K^4)

The energy loss through the bottom of the collector is mainly due to conduction through insulation and is therefore given by:

$$U_b = k/l \quad (37)$$

Where k is the insulation thermal conductivity in W/m K and l is the insulation thickness in m.

The edge losses are estimated by assuming one dimensional sideways heat flow around the perimeter of the collector. The edge loss coefficient based on the collector area is, [1]:

$$U_e = (UA)_{edge}/A_c$$

For unit area of the collector, $A_c = 1$ and,

$$U_e = UA \quad (38)$$

Where $U = k/l$, and A is the area of the edges.

The collector overall loss coefficient U_L is the sum of the three components i.e.

$$U_L = U_t + U_b + U_e \quad (39)$$

Useful Energy Gain of a Collector Model

The equations derived in the preceding sections for flat plate collectors are based on a collector of unit area. I.e. $A_c = 1$. In this analysis a collector model of surface area A_m is considered. If a model ratio is defined as: $r_m = A_m + A_c$ then, the above mentioned equations must be multiplied by the model ratio, r_m , so that, they can be used for the collector model. The useful solar energy gain of the collector model is simulated by an electrical heater which gives the same quantity of heat as the useful gain of the model. The heat energy is then transferred to the aqua-ammonia solution in the generator through a shell type heat exchanger, so, using equation (35), the actual heat received by the solution is given by:

$$Q_u = r_m \{S - 3600 U_L (T_{pm} - T_a)\} \quad (40)$$

3. Generator Analysis

The generator contains aqua-ammonia solution, and is heated by solar energy, Fig. 3. Assume the initial state, when heat starts to transfer to the solution, is given by:

T_{s1} = initial temperature of the solution

x_{11} = initial concentration of ammonia in the solution

h_{11} = initial enthalpy of the solution

P_{11} = initial pressure of the solution

After one hour, a certain quantity of heat is transferred to the solution and the new state of the solution is given by:

T_{s2} = the temperature of the solution after one hour

x_{12} = the concentration of ammonia in the solution after one hour

h_{12} = the enthalpy of the solution after one hour

P_{12} = the pressure of the solution after one hour

Assume that, the saturation pressure of the solution, which corresponds to the condenser temperature, is, P_{sat} , and the corresponding temperature of the solution, at the initial concentration, is, T_{sat} .

In writing the generator subroutine, to find the properties of the solution at the end of an hour, and the quantity and properties of ammonia vapor which is generated during that hour, three cases regarding initial heating of the solution, must be considered. After one hour from the beginning of the regeneration cycle, the solution temperature increases to a value, which may be less than, greater than or equal to the saturation temperature of the solution, at the initial concentration.

First Case: The temperature of the solution at the end of an hour, is less than the saturation temperature: If, after one hour of heating, the solution temperature, T_{s2} , is less than the saturation temperature of the solution, then no ammonia will be generated and the whole energy, Q_u , is used to raise the solution temperature from T_{s1} to T_{s2} .

Using equation (40), the energy balance equation is therefore:

$$m_s c p_s (T_{s2} - T_{s1}) = r_m \{ S - 3600 U_L (T_{s2} + T_{s1}) / 2 - T_a \} \quad (1)$$

From which:

$$T_{s2} = r_m \left\{ S + \left(\left(\frac{m_s c p_s}{r_m} \right) - 1800 U_L \right) T_{s1} + 3600 U_L T_a \right\} / (m_s c p_s + 1800 U_L r_m) \quad (2)$$

Where $c p_s$ is the specific heat of the solution in J/kgK and m_s is its mass. In this case the concentration of ammonia in the solution, x_{11} , remains unchanged. The enthalpy and the pressure of the solution, however, will have new values h_{12} and P_{12} respectively which can be found from the enthalpy-concentration chart, at a temperature, T_{s2} , and a concentration $x_{12} = x_{11}$, [3].

Second Case: The temperature of the solution at the end of an hour, is greater than the saturation temperature. If the final temperature of the solution at the end of an hour, T_{s2} , is greater than the saturation temperature at the initial concentration, this means that part of the useful energy, Q_u , available during that hour, is used to raise the

temperature of the solution to T_{s2} and the remaining part is used to generate ammonia vapor. Initially, the solution temperature starts to increase and consequently the solution pressure and enthalpy. This continues until the solution temperature reaches the saturation temperature, at the given concentration, after that, the temperature increases at constant pressure which is the saturation pressure, and ammonia starts to evaporate, and hence the concentration of the solution, decreases.

In this case, it is necessary to calculate the fraction of the total energy available, for the given hour, which is used to raise the solution temperature to the saturation temperature, and since the rate of energy is assumed to be uniform throughout each hour, this fraction also gives the period of time required for the solution temperature to reach the saturation temperature. Let U_r to represent this period, hence the fraction of the absorbed solar energy during this period is:

$$q_1 = U_r S \quad (3)$$

To be able to use the energy balance equation, (equation (1)), the thermal loss term must be multiplied by the fraction U_r , to get the losses during the same period. Equation (1), then, becomes:

$$m_s c p_s (T_{sat} - T_{s1}) = r_m U_r \left\{ S - 3600 U_L \left\{ \frac{(T_{sat} + T_{s1})}{2} - T_a \right\} \right\} \quad (4)$$

From which:

$$U_r = m_s c p_s (T_{sat} - T_{s1}) / r_m \left\{ S - 3600 U_L \left\{ \frac{(T_{sat} + T_{s1})}{2} - T_a \right\} \right\} \quad (5)$$

For the rest of the hour, the remaining fraction of energy $(1 - U_r)S$ is used to raise the solution temperature from T_{sat} to T_{s2} at constant pressure, P_{sat} , and at the same time, to generate ammonia vapour, so the energy balance equation for this case is:

$$m_s c p_s (T_{s2} - T_{sat}) + m_v h_v = r_m (1 - U_r) \left\{ S - 3600 U_L (T_{sat} + T_{s2}) / 2 - T_a \right\} \quad (6)$$

Where m_v is the mass of the ammonia vapor generated during the period $(1 - U_r)$, and h_v , is the enthalpy of the generated vapor, in J/kg.

From equation (6) the temperature of the solution at the end of the hour can be found as:

$$T_{s2} = \left\{ r_m (1 - U_r) \left\{ S - 1800 U_L (T_{sat} - 2T_a) \right\} + m_s c p_s T_{sat} + 1800 U_L r_m \right\} - m_v h_v / \left\{ m_s c p_s + 1800 (1 - U_r) U_L r_m \right\} \quad (7)$$

Knowing the temperature T_{s2} , the properties of the aqua-ammonia solution, and evaporated ammonia, at the end of the hour, can be found, at the saturation pressure of the solution, P_{sat} . These include:

x_{12} = the concentration of ammonia in the solution

h_{12} = the enthalpy of the solution

x_{v2} = the concentration of the ammonia vapor

h_{v2} = the enthalpy of the ammonia vapor

The mass of the generated ammonia vapor during the given period can be calculated from the relation, [3]:

$$m_{v2} = m_{s1}(x_{11} - x_{12})/(x_{v2} - x_{12}) \quad (8)$$

And the mass of the remaining solution, at the end of the hour, is given by the relation:

$$m_{s2} = m_{s1}(x_{v2} - x_{11})/(x_{v2} - x_{12}) \quad (9)$$

The amount of water vapor contained in the evaporated ammonia is given by:

$$m_{w2} = m_{v2}(1 - x_{v2}) \quad (10)$$

Third Case: The temperature of the solution at the end of an hour equals the saturation temperature. If the final temperature, T_{s2} , of the solution at the end of an hour, as obtained from equation (2) equals the saturation temperature of the solution, then, for the next hour, the available energy, is used to generate ammonia vapor, and to raise the temperature of the remaining solution. In this case the energy balance equation which must be used is:

$$m_s cp_s (T_{s2} - T_{s1}) + m_v h_v = r_m \{ S - 3.6 U_L \left\{ \frac{(T_{s2} + T_{s1})}{2} - T_a \right\} \} \quad (11)$$

From this equation the temperature of the solution after one hour, T_{s2} can be written as:

$$T_{s2} = \{ r_m (S - 1800 U_L T_{s1} + 3600 U_L T_a) + m_s cp_s T_{s1} - m_v h_v \} / \{ m_s cp_s + 1800 U_L r_m \} \quad (12)$$

The regeneration cycle continues until the solar energy absorbed by the absorber plate, S , is less than the thermal losses. Practically, the regeneration cycle must be terminated when the concentration of the generated ammonia falls below a specific value, so that water content in the ammonia vapor is at a maximum allowable limit. This is accomplished by adjusting the slope angle of the collector, such that, when the concentration of the generated ammonia vapor, is less than the specific value, after a given period from the beginning of the regeneration cycle, then the solar energy absorbed will be less than the thermal losses and no vapor will be generated.

4. Condenser Analysis

During the regeneration cycle, the generated ammonia vapor is condensed and stored in the receiver, at a temperature, T_{cd} , and pressure, P_{cd} . The condenser tank, Fig. (4), is in the form of a rectangular shallow basin, full of water, insulated from the bottom and edges, and left open to the atmosphere during the night. Due to sky cooling, the water in the basin is cooled and used as a cooling medium for the generated ammonia vapor.

The Quantity of Heat to be removed in the Condenser

In the generator, a quantity of ammonia vapor, v m kg, is evaporated during one hour of generation. This vapor, which is at temperature, T_{s2} , passes through the condenser. The condenser consists of a coil of a tube, submerged in the cold water in the condenser tank. The condenser is required to cool ammonia vapor from temperature, T_{s2} , and enthalpy h_{v2} (J/kg), and condense it to a liquid at temperature T_{cd} , and enthalpy h_{cd} (J/kg). The quantity of heat in J, which must be removed from ammonia vapor during that hour is, therefore, given by:

$$Q_{hr} = m_v(h_{v2} - h_{cd}) \quad (1)$$

Required Surface Area of Condenser Tube

The condenser consists of a tube coil of length, L_t , and diameter, d . The total surface area is therefore:

$$A = \pi dL_t \quad (2)$$

Where d is the outer diameter of the tube. The rate of heat transfer, in W, is given by:

$$\dot{Q} = hA\Delta T \quad (3)$$

Where, ΔT is the temperature difference and is given by:

$$\Delta T = T_{st} - T_{cc} \quad (4)$$

T_{st} , is the saturation temperature of the ammonia vapor at the saturation pressure, P_{sat} , and T_{cc} is the surface temperature of the tubes, which is taken the same as the temperature of the cold water in the basin. h , is the average heat transfer coefficient for condensation and is given by:

$$h = Nu k / d_i \quad (5)$$

Where, k is the thermal conductivity of the ammonia film, d_i is the inner diameter of the tube, Nu is the Nusselt number for condensation and is given by, [5]:

$$Nu = 1.03(h_{fg}\rho^2gd_i^3/4\mu k\Delta T)^{1/4} \quad (6)$$

Where, h_{fg} is the latent heat of ammonia vapour at P_{sat} . ρ is the density of ammonia film taken at the average film temperature, μ is the viscosity of ammonia film taken at the average film temperature, and g is the gravitational acceleration.

From equations (1), (2) and (3) the required surface area, and hence the required tube length, can be found:

$$A = \dot{Q} / h\Delta T = Q_{hr}/3600h\Delta T = m_v(h_{v2} - h_{cd})/3600h\Delta T \quad (7)$$

And,

$$L_t = A/\pi d \quad (8)$$

Mass of Cooling Water Required in the Condenser

During one hour period, the quantity of heat absorbed by cold water in the condenser is the same as the quantity of heat rejected by the ammonia vapor so the energy balance equation in the condenser is:

$$m_{cw}cp_w\Delta T_{cw} = m_v(h_{v2} - h_{cd}) \quad (9)$$

From which,

$$m_{cw} = m_v(h_{v2} - h_{cd})/ cp_w\Delta T_{cw} \quad (10)$$

Where, m_{cw} is the mass of the cooling water required in the condenser, in kg, cp_w is the specific heat of the cooling water in J/kgC and ΔT_{cw} is the rise in temperature, in °C, of the cold water after one hour.

5. Absorber Analysis

After the regeneration cycle has been completed, there will be a certain quantity of ammonia m_{vt} , evaporated, condensed and stored in the receiver, at known condenser pressure P_{cd} and temperature T_{cd} . The weak solution in the generator will be at a temperature equals the temperature of the solution at the end of the regeneration cycle, T_{s2} . The mass of the weak solution \dot{m}_{s2} equals the original mass of the strong solution minus the total mass of the evaporated ammonia m_{vt} including water content.

Sudden Cooling of Generator

In the absorption cycle the generator will be converted to act as an absorber. The absorption cycle starts with a sudden cooling of the generator by allowing cooling water to pass through the tubes inside the generator. The objective of the sudden cooling process is to lower the weak solution temperature from T_{s2} to the required absorption temperature, T_{abs} . This also lowers the pressure of the solution. This action is equivalent to a throttling process, and can be termed, thermal throttling, no mechanical throttling valve is required.

The sudden cooling of the generator is accomplished by allowing large quantity of cooling water to flow through the tubes inside the generator. The initial temperature of the weak solution for the sudden cooling process is assumed to be the same as the temperature of the weak solution at the end of the regeneration cycle T_{s2} , and the final

temperature equals the required absorption temperature, T_{abs} . The properties of the weak solution, which include density, specific heat, viscosity, thermal conductivity and Prandtl number, are evaluated, at an average temperature given by :

$$T_{av1} = (T_{s2} + T_{abs})/2 \quad (1)$$

These properties are determined as follows: From tables of properties of fluids, [19], [20], the specific property for pure ammonia, Pr_a , and for water, Pr_w , can be found at a temperature, T_{av1} , the value of the corresponding property of the aqua-ammonia solution, Pr_s , can then be found from the relation:

$$Pr_s = (1 - x_s)Pr_w + x_sPr_a \quad (2)$$

Where, x_s is the concentration of ammonia in the solution.

At the beginning of the sudden cooling process, x_s is the same as the concentration at the end of the regeneration cycle, x_{L2} . The properties of the cooling water are evaluated, at an average temperature given by:

$$T_{av2} = (T_{cwi} + T_{cwo})/2 \quad (3)$$

Where,

T_{cwi} = the inlet cooling water temperature.

T_{cwo} = the outlet cooling water temperature.

Rate of Heat Transfer during Sudden Cooling

During sudden cooling of the generator, which is converted now, to act as an absorber, heat is transferred from the weak solution to the cooling water. The rate of heat transfer in W, is given by, [19], [21]:

$$\dot{Q}_1 = UA\Delta T \quad (4)$$

Where, U is the overall heat transfer coefficient (in W/m²K) and is given by:

$$1/U = 1/h_{1p} + \delta/k + 1/h_{2p} \quad (5)$$

h_{1p} is the heat transfer coefficient for the weak solution (outside the tubes), and h_{2p} is the heat transfer coefficient for cooling water (inside the tubes). Fig. 7 below shows heat transfer during sudden cooling of the generator.

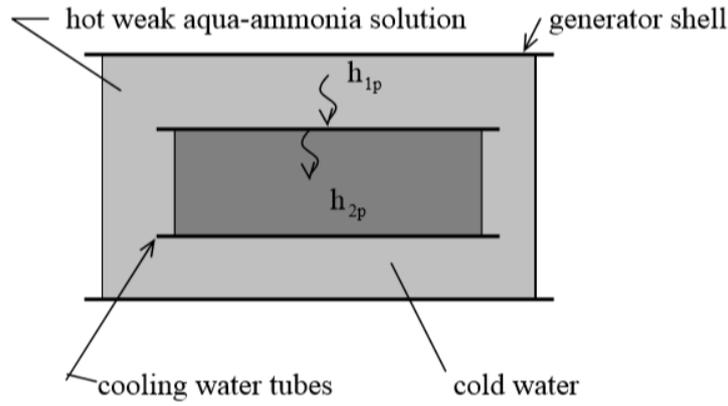


Fig. 7 Heat Transfer during Sudden Cooling of the Generator

δ is the thickness of the tube

k is the thermal conductivity of the tube material

A is the mean surface area given by:

$$A = \pi d_m L_t n \quad (6)$$

Where:

d_m is the mean diameter of the tubes

L_t is the length of a single tube

n is number of tubes inside the shell

ΔT is the logarithmic mean temperature difference, which is given by the following expression [19]:

$$\Delta T = \frac{\{(T_{abs} - T_{cwo}) - (T_{s2} - T_{cwi})\}}{\ln\{(T_{abs} - T_{cwo}) / (T_{s2} - T_{cwi})\}} \quad (7)$$

As the tube thickness is small, the conduction term, δ/k in equation (5) can be neglected, so that the overall heat transfer coefficient in this case is given by:

$$1/U = 1/h_{1p} + 1/h_{2p} \quad (8)$$

The heat transfer coefficient, h , is found from the equation:

$$h = Nu k / d \quad (9)$$

Where, d is the corresponding diameter of the tube. Nu is the Nusselt number and is given by the following equation, [5]:

$$Nu = 0.527 Pr^{1/2} \left(Pr + \frac{20}{21} \right)^{-1/4} Gr^{1/4} \quad (10)$$

Where, Gr is the Grashof number and Pr is the Prandtl number. These are given by the following expressions:

$$Gr = (\rho^2 d^3 g \beta \theta) / \mu^2 \quad (11)$$

$$Pr = (cp \mu) / k \quad (12)$$

Where, ρ is the density of the fluid; d is the diameter of the tube; g is the gravitational acceleration; β is the coefficient of thermal expansion; θ is the temperature difference between the fluid and the tube surface; μ is the dynamic viscosity of the fluid; cp is the specific heat of the fluid and k is the thermal conductivity of the fluid.

The heat transfer coefficients, are, therefore, given by:

$$h_{1p} = Nu_s k_s / d_o \quad (13)$$

Where, k_s , is the thermal conductivity of the aqua-ammonia solution.

$$h_{2p} = Nu_w k_w / d_i \quad (14)$$

And, k_w , is the thermal conductivity of the cooling water. The subscripts, s and w , refer to aqua-ammonia solution and cooling water respectively.

d_o is the outer diameter of the tube. d_i is the inner diameter of the tube.

The difference between the mean temperature of the solution, T_{av1} , and the surface temperature of the tube, T_b , is given by:

$$\theta_s = T_{av1} - T_b \quad (15)$$

And the difference between the surface temperature of the tube, and the mean temperature of the cooling water, T_{av2} , is given by:

$$\theta_w = T_b - T_{av2} \quad (16)$$

Mass Flow Rate of Cooling Water and Time Duration for the Sudden Cooling Process

During the sudden cooling process, the cooling water is required to cool the weak solution from the temperature of the solution at the end of the regeneration cycle, T_{s2} , to the required absorption temperature, T_{abs} . The total quantity of heat, in Joules, to be removed by the cooling water during the sudden cooling process is, therefore:

$$Q_2 = m_{s2}(h_i - h_f) \quad (17)$$

Where, m_{s2} is the mass of the weak solution at the end of the regeneration cycle, h_i is the enthalpy of the weak solution, at the beginning of the sudden cooling process, in J/kg. This is same as the enthalpy of the aqua- ammonia solution, at the end of the regeneration cycle, and is obtained from h-x chart, [3], at the saturation pressure of the solution, P_{sat} , and temperature T_{s2} , h_f is the enthalpy of the weak solution, in

J/kg, at the end of the sudden cooling process, and is obtained from the h-x chart, at temperature T_{abs} and concentration x_{L2} . x_{L2} is the concentration of ammonia in the weak solution at the end of the regeneration cycle. The period in seconds of the sudden cooling process, t_{sc} , can be found from equations (4) and (17) as:

$$t_{sc} = Q/\dot{Q}_1 \quad (18)$$

The quantity of heat which must be removed by cooling water during the sudden cooling process is also given by:

$$Q_2 = m_{tcw}cp\Delta T_4 \quad (19)$$

Where, m_{tcw} is the total mass of the cooling water required, in kg, cp is the specific heat of the cooling water, in J/kg°C. ΔT_4 is the increase of the cooling water temperature, in °C.

From equation (19), the total mass of the cooling water required for the sudden cooling is:

$$m_{tcw} = Q_2/cp\Delta T_4 \quad (20)$$

Where, Q_2 is given by equation (17). Hence, the mass flow rate of the cooling water, during the sudden cooling process, is given by:

$$\dot{m}_{cw} = m_{tcw}/t_{sc} \quad (21)$$

Absorption Cycle

By the end of the sudden cooling process, the temperature and pressure of the weak solution will be lowered to the minimum values corresponding to the required absorption temperature. Pure ammonia, which is stored at high pressure P_{cd} in the receiver, will start to evaporate and flow back, to be absorbed by the weak solution in the absorber, and hence produce the cooling effect required in the receiver. The generator, now, acts as an absorber, and the receiver, as an evaporator. The absorption process increases concentration, temperature and pressure of the weak solution. The temperature, however, must be maintained constant, at the required absorption temperature, by continuous cooling of the absorber. The absorption cycle must continue until the whole ammonia is returned back from the evaporator and absorbed by the weak solution in the absorber. The solution pressure, P_s in the absorber must always be less than the pressure in the evaporator, P_c . This is attained by controlling the rate of cooling of absorber. The absorption cycle must extend for the rest of the day, after the regeneration cycle has been completed.

Rate of Heat Transfer during Absorption Process

When ammonia vapor is absorbed by the weak aqua-ammonia solution in the absorber, a quantity of heat Δh will be released and hence the solution temperature will increase.

This heat is known as the heat of the absorption. To maintain the solution temperature to the required absorption temperature, continuous cooling of the absorber is required. This is accomplished by allowing cooling water to flow, at a specific rate, through the tubes inside the absorber. The properties of the weak solution, namely: density, viscosity, specific heat, thermal conductivity and Prandtl number, are found from equation (2) by using the corresponding properties of water and pure ammonia which are obtained from tables of properties, [19], [20], at the absorption temperature. The rate of heat transfer, during the absorption process, is given by:

$$\dot{Q}_a = UA\Delta T_{3a} \quad (22)$$

Where A is the mean surface area of the tubes as given by equation (6), U is the overall heat transfer coefficient, and is given by the equation:

$$1/U = 1/h_1 + 1/h_2 \quad (23)$$

Where, h_1 and h_2 , are the heat transfer coefficients for the weak solution, and cooling water, respectively, during the absorption process, and are found by using equations (13) and (14), where the properties of the weak solution, are evaluated at the absorption temperature, T_{abs} , and that of the cooling water at temperature T_{av2} . The total quantity of heat, in Joules, which can be transferred during one hour of absorption, is given by:

$$Heat\ 1 = 3600 UA\Delta T_{3a} \quad (24)$$

Heat of Absorption and Mass Flow Rate of Cooling Water

During the absorption process ammonia vapor, which is at enthalpy h_g · J/kg, flows at a rate \dot{m}_{av} and is absorbed by the weak solution of initial concentration x_{s1} , and enthalpy, h_{s1} , respectively. Considering one hour duration, the energy balance equation, is therefore [3].

$$m_{s1}h_{s1} + m_{av}h_g = h_{f1}m_{s2} \quad (25)$$

Where, m_{s1} is the initial total mass of the solution, m_{av} is the mass of ammonia vapour, which is absorbed during one hour of absorption. Knowing the total mass, in kg, of ammonia liquid, which is stored in the receiver, m_{avt} , and the period, in hours, of absorption cycle, P_{abs} , then m_{av} can be found from the relation:

$$m_{av} = m_{avt} / P_{abs} \quad (26)$$

m_{s2} is the total mass of the solution, at the end of one hour of absorption, and is given by:

$$m_{s2} = m_{s1} + m_{av} \quad (27)$$

h_{f1} is the final enthalpy, in J/kg, of the solution after one hour. From equations (25), (26) and (27) h_{f1} can be written as:

$$h_{f1} = h_{s1} + m_{av}(h_g - h_{s1})/m_{s2} \quad (28)$$

Equation (28) gives the enthalpy that the weak solution would have after one hour of absorption, if there was no cooling. Due to cooling, the enthalpy of the solution will be reduced to a value h_{f2} , corresponding to the absorption temperature T_{abs} , and the new value of concentration of the solution x_{s2} which is given by:

$$x_{s2} = x_{s1} + m_{av}(x_v - x_{s1})/m_{s2} \quad (29)$$

x_v , is the concentration of ammonia vapour which is taken as unity (pure ammonia). The heat of absorption in, joules, is therefore given by:

$$Heat\ 2 = m_{s2}(h_{f1} - h_{f2}) \quad (30)$$

h_{f2} Can be found from the h-x chart, at concentration x_{s2} , and temperature T_{abs} .

Equation (30) gives the quantity of heat which must be removed by cooling water during one hour of absorption. From equations (24) and (30) the required surface area of the tubes can be found:

$$A = Heat\ 2 / 3600 U \Delta T_{3a} \quad (31)$$

And hence, the length of each tube is:

$$L_{tg} = A / \pi d_m n_a \quad (32)$$

Where, n_a , is the number of tubes inside the absorber. The quantity of heat given by equation (30), must be removed by the cooling water, during one hour, hence,

$$3600 \dot{m}_{cwa} cp_w \Delta T_{cwa} = m_{s2}(h_{f1} - h_{f2}) \quad (33)$$

Where, \dot{m}_{cwa} is the mass flow rate of cooling water during absorption.

Therefore:

$$\dot{m}_{cwa} = m_{s2}(h_{f1} - h_{f2}) / 3600 cp_w \Delta T_{cwa} \quad (34)$$

Where, cp_w , is the specific heat, in J/kg°C, of the cooling water, and ΔT_{cwa} , is the increase in cooling water temperature, in °C, during the absorption cycle.

During the absorption process the concentration of ammonia in the solution increases. The temperature of the solution is maintained constant at the required absorption temperature by cooling the solution. The pressure, however, will increase. The solution pressure at the end of one hour of absorption, P_s , is found from the h-x chart,[3], at the absorption temperature, T_{abs} , and concentration x_{s2} , using the least square method of curve fitting, [18].

5. Evaporator Analysis

When the pressure of the weak solution is lowered due to the sudden cooling of the generator, which now acts as an absorber, the ammonia liquid in the receiver, which is at a higher pressure, P_c , will start to evaporate, and hence remove heat from surroundings, and flow back, to be absorbed by the weak solution in the absorber. Due to absorption, the pressure and temperature of the aqua-ammonia solution in the absorber will increase and due to evaporation of pure ammonia, the pressure and temperature in the evaporator will decrease. The flow of ammonia vapor, from the evaporator to the absorber, will continue as long as the solution pressure in the absorber, is less than the pressure of pure ammonia in the evaporator, or until no more ammonia remains in the evaporator. So, the evaporation and absorption stages occur simultaneously.

Evaluation of Pressure and Temperature in the Evaporator

The quantity of heat absorbed by evaporated ammonia, in the evaporator, during one hour, equals the quantity of heat removed from pure ammonia liquid in the receiver, and from the water surrounding the receiver, during the same hour. The energy balance equation is therefore:

$$m_{av} h_{fg} = cp_a m_{ca}(T_{c1} - T_{c2}) + cp_w m_{eq}(T_{c1} - T_{c2}) \quad (1)$$

Where, T_{c1} and T_{c2} are the initial and final temperatures, in the receiver, cp_a and cp_w , are specific heats of pure ammonia, and cold water, respectively at an average temperature given by:

$$T_{av} = (T_{c1} + T_{c2})/2 \quad (2)$$

m_{eq} , is the equivalent mass of the cold water, accounting for the metal in the evaporator. m_{ca} , is the total mass of the remaining liquid of pure ammonia in the evaporator. h_{fg} , is the latent heat of evaporation of pure ammonia, at the evaporator pressure, P_c . m_{av} , is the mass of ammonia vapour, which is transferred from the evaporator to the absorber during one hour, as given by equation (26). The equivalent mass, m_{eq} , can be found from the relation:

$$m_{eq}cp_w = m_w cp_w + m_{metal}cp_{metal} \quad (3)$$

Or,

$$m_{eq}cp_w = cp_w(m_w + \frac{m_{metal}cp_{metal}}{cp_w}) \quad (4)$$

Therefore,

$$m_{eq} = m_w + \frac{m_{metal}cp_{metal}}{cp_w} \quad (5)$$

From equation (1), the temperature in the evaporator after one hour is therefore:

$$T_{c2} = T_{c1} - m_{av} h_{fg} / (m_{ca} cp_a + m_{eq} cp_w) \quad (6)$$

7. The Simulation Program

Using the equations derived, in previous sections, for individual components, the simulation computer program, was written for solar absorption refrigeration systems, which use ammonia as a refrigerant, in an intermittent cycle. The least square method of curve fitting, [18], is used in the program, to evaluate the properties of the fluids involved. The user is asked to enter data concerning: size, site, date, available cooling water temperature and the required absorption temperature. The program consists of a number of subroutines and the output is divided into five parts:

The first part of the program gives the following output:

- 1- The quantity of solar energy absorbed by the flat plate collector during each hour of the regeneration cycle.
- 2- The temperature, pressure, concentration and enthalpy of the aqua-ammonia solution at the end of each hour of the regeneration cycle.
- 3- The quantity of ammonia evaporated, its enthalpy and concentration at the end of each hour of the regeneration cycle.
- 4- The quantity of water content in the ammonia vapor at the end of each hour of the regeneration cycle, and the total water present at the end of the regeneration cycle.

The second part gives the required size of the condenser and the quantity of the cooling water required for condensation stage.

The third part gives the following results:

- 1- Time duration of the sudden cooling prior to absorption stage.
- 2- The mass flow rate and the total mass of the cooling water required for the sudden cooling process.

The fourth part of the program gives the following output:

- 1- The mass flow rate and the total mass of the cooling water required for the absorption cycle.
- 2- The pressure and temperature of aqua-ammonia solution at the end of each hour of the absorption cycle.

The fifth part of the program gives the temperature and pressure in the Evaporator, at the end of each hour of the absorption cycle. This part stops the program whenever the solution pressure becomes larger than the evaporator pressure or no more ammonia remains in the evaporator.

IV. DESIGN AND CONSTRUCTION OF THE SYSTEM MODEL

1. Specifications

The design process of the system model is carried out on the basis of a set of specifications which have been prepared according to the British Standard recommendations BS PD 6112, [22]. The details of these specifications are as follows:

History and Background

Dependence of the world on petroleum as a main source of energy, results in an increasing rate of consumption of petroleum. Bearing in mind that, petroleum is a limited source of energy, there must be an end to this source. This fact indicates that alternative sources of energy must be provided, to reduce the rate of consumption of petroleum to a minimum. Solar energy is one of the most important renewable sources of energy to be used. One of the most suitable fields of application of solar energy, is refrigeration, either for comfort or for food preservation. The appropriate method of utilization of solar energy for this field of application in tropical climates is the thermal conversion method, since it provides heat energy, which can be used directly to drive absorption refrigeration systems. Another factor, which encourages use of thermal conversion method in tropical climates, is the high intensity of solar radiation. However, to arrive to a suitable design for a solar refrigeration system, at a minimum cost, a lot of studies and research work must be carried out. This indicates a need for a model, which can be used by researchers and students to carryout experiments concerning solar absorption refrigeration systems, under varying conditions of operation. Since long terms experiments are expected, and experimental data are to be recorded on hour basis, an indoor model is required, so that it can be located inside a laboratory, instead of outdoors under the sunlight. This will, largely, facilitate the experimental work. Ammonia-water system is to be used, since it gives lower temperature in the cold space compared with lithium bromide-water system. Since liquids in this system flow by gravity, the model must be properly leveled, using a level indicating device. Furthermore, it is recommended that, the model be compact, rigid and stable, so that accurate results can be obtained. Welded steel fabrication from tube, plate, angle sections or combination of each are to be used. The whole structure is to be of minimum material, while maintaining the strength and stiffness for the conditions of use.

Scope of Specification

The model must be designed to generate a suitable quantity of refrigerant vapor so that accurate data can be obtained. This will fix the capacity of the condensate tank, which is estimated to be about 0.2 kg, of pure ammonia liquid. Other components of the model are to be sized accordingly. The highest working pressure in the model is to be about 15 bar and the cooling water is expected to be available at a temperature of about 20°C. To avoid reaction of ammonia, only steel or aluminum is to be used for tubes, gauges, fittings and valves.

Conditions of Use

The model must enable use of varying quantities of pure ammonia, distilled water and cooling water in addition to a varying heat energy input. Such quantities must be easily added and controlled to the required values. There must be two pressure gauges to indicate the pressure in generator/absorber and receiver/evaporator components. When in use, the system must be properly leveled, but it must allow the tilting of the generator/absorber, condenser and receiver/evaporator units, so that water contents in ammonia liquid can be returned back to the generator/absorber unit, every about ten working days.

Characteristics

Heating unit:

This is required to act as a solar collector, which provides heat energy to the system. Electrical energy source of 220 V, is to be used. The whole unit must be insulated and provided with controlling valves and a means of measuring the temperature of the hot water. The control valves must be positioned so that, the unit will be easily operated and controlled. Galvanized tubes are to be used for the tubing. Generator/absorber: This is to be a thick, horizontal steel pipe, with closed ends and thermally insulated, to hold ammonia-water solution. Three tubes of smaller diameter, are to be located properly inside this pipe, to be used for heating or cooling of the solution. Fittings for three valves are to be included. The functions of these valves are as follows: The first valve is to be used to read the generator pressure, during the regeneration cycle, or absorber pressure, during the absorption cycle. The second valve is to be used to add solution or to purge ammonia vapor when excess pressure has encountered in the system. The third valve is for removal of the solution when repairs are required. In addition a fitting for another tube is to be provided. This is a vertical tube, which is to be used to transfer ammonia vapor, from the generator, during the regeneration cycle, or to the absorber, during the absorption cycle to the condenser coil. This tube is provided with a valve to control the flow of ammonia vapor. The generator/absorber is to be designed so that it can easily be leveled; a level-indicating device must be fitted.

Condenser:

This is a thick steel tube in a form of a coil, immersed in a cooling water which is contained in a tank. When ammonia vapor enters this coil it starts to transfer to a liquid. So the condenser coil must be designed so that, liquid ammonia can flow, under gravity, towards the receiver. The condenser cooling water tank is to be rigid so as to support the condenser coil. It must be insulated from bottom and edges and provided with a drain tube to drain cooling water for cleaning. This tank is to be carried on a rigid steel fabrication frame, from angles and plates, and must be designed so, that it can be tilted to return back water contents, from the receiver to the generator, as required.

Receiver:

This is to be a thick steel tube, concentric within a larger galvanized one, the space between the two tubes is to be filled with water to be cooled during absorption cycle. The whole assembly is to be insulated and inclined at a suitable angle so that liquid ammonia can flow easily from the condenser coil to the receiver, under gravity. Fittings for two valves must be provided. The first valve is to be used on request to control the flow of ammonia vapor during absorption cycle. The second valve is to be used to check the pressure inside the receiver. The outer tube, which contains cold water, is to be provided with two fittings, one of them is to be used, for measuring the cold water temperature, during the absorption cycle. The other one is to be used, to drain cold water on request.

Frame:

This is required to support all the system components. It is to be welded steel fabrication from plate and angle section. The structure is to maintain strength and stiffness for the conditions of use and is to be provided with pivots about which, generator, condenser cooling water tank, condenser coil and receiver can be tilted, as one unit.

Absorption Cooling Water Tank:

This is to be used to store cooling water for absorption cycle. It is to be insulated from bottom and edges and provided with valves to control flow rate of cooling water. Welded steel plates and angles are to be used. Cooling water outlet from this tank must be at a higher level, relative to cooling water inlet to the absorber so that, cooling water can flow by gravity.

Ergonomic Considerations

For functioning purposes, the condenser cooling water tank is to be the highest component in the system and the generator/absorber is the lowest component. The size and height of the system components must be such that, researchers and students can easily watch and read the required experimental data from different components, in addition, cooling water or ammonia-water solution must be easily added or discharged from the system.

Appearance

The system model should be stable and symmetrical, and give the impression of precision and efficiency of operation. Sharp corners in the structure are to be rounded and steel surfaces must be coated with prime and paint, for protection against weather, and are to be flat to aid cleaning. Cooling water tanks are to be colored with a reflecting color, so as not to absorb heat from surroundings.

Performance

The system model must be tested for leakage under similar conditions to those expected in the experimental work.

V. EXPERIMENTAL WORK

1. Apparatus

The complete apparatus, which is shown schematically in Fig. 1, consists of the following components:

Generator/Absorber

This is a single vessel performing both functions of generator, during the regeneration cycle, and, absorber, during the absorption cycle. It is a thick pipe of 100 mm inside diameter and 10 mm thick, it has an effective length of 0.72 m. The ends of this pipe are closed by two end plates, which are welded to the pipe and connected together by means of three tubes, each one of these tubes is 16mm inner diameter and 22 mm outer diameter. These tubes, which are welded to the end plates, are connected end to end by means of drills made through the end plates. These tubes form a coil through which hot water pass from the heating unit, when the vessel acts as a generator. The same tubes carry cooling water, which enter from the cooling water tank, when the vessel acts as an absorber.

During the regeneration cycle, heat is transferred from the hot water, which is circulating through the tubes of the generator, to the aqua ammonia solution, which is contained in the generator, hence the temperature and pressure of the aqua-ammonia solution will increase. When the solution pressure reaches the saturation pressure, which corresponds to the condenser temperature, ammonia vapor will start to rise up, and hence the concentration of the solution decreases, the temperature increases and the pressure remains constant.

During the absorption cycle, heat is transferred from the aqua-ammonia solution in the absorber to the cooling water, which is circulating inside the tubes of the absorber. Hence, the temperature and pressure of the solution will decrease. This allows ammonia liquid to vaporize in the evaporator, and hence produce cooling effect there, and flow back to be absorbed by the weak solution in the absorber. Due to absorption, the concentration of the solution increases, the temperature, however remains constant due to continuous cooling of the absorber, and the pressure increases slightly.

A vertical tube of 16mm inner diameter and 22mm outer diameter rises from the generator/absorber to the condenser. This tube carries ammonia vapor, which is generated during the regeneration cycle, to the condenser. The same tube carries ammonia vapor, which evaporates in the evaporator, to be absorbed back in the absorber during the absorption cycle. This vertical tube is provided with a valve, to control the flow of ammonia vapor. The generator/absorber is also provided with a pressure gauge, charging valve and a drain plug.

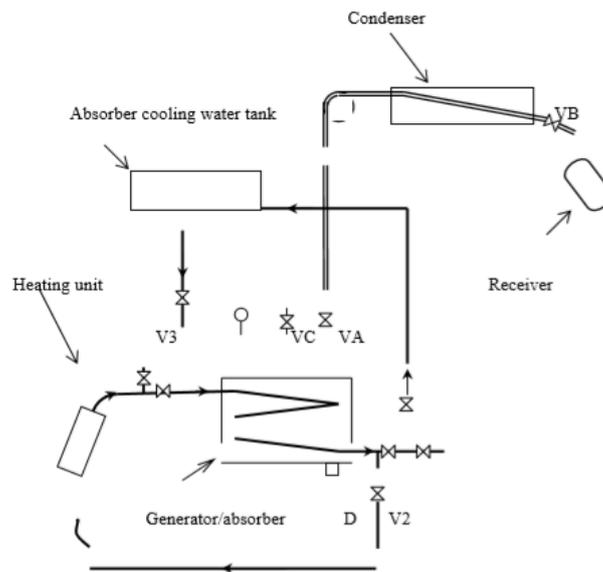


Fig. 1 Schematic Diagram of the Apparatus

The tubes of the absorber. Hence, the temperature and pressure of the solution will decrease. This allows ammonia liquid to vaporize in the evaporator, and hence produce cooling effect there, and flow back to be absorbed by the weak solution in the absorber. Due to absorption, the concentration of the solution increases, the temperature, however remains constant due to continuous cooling of the absorber, and the pressure increases slightly.

A vertical tube of 16mm inner diameter and 22mm outer diameter rises from the generator/absorber to the condenser. This tube carries ammonia vapor, which is generated during the regeneration cycle, to the condenser. The same tube carries ammonia vapor, which evaporates in the evaporator, to be absorbed back in the absorber during the absorption cycle. This vertical tube is provided with a valve, to control the flow of ammonia vapor. The generator/absorber is also provided with a pressure gauge, charging valve and a drain plug.

Condenser

The condenser is a coil of a tube, which is 16 mm inner diameter and 22 mm outer diameter, immersed in cold water, which is contained in a tank, 0.7 m wide and 0.8 m long. The depth of water in the condenser tank can be varied from about 30 mm up to 100mm. The condenser coil is fitted to two end joints. The inlet end joint is connected to the vertical tube, rising from the generator/absorber, and the outlet end joint is connected to the receiver. The condenser coil is sloping down towards the outlet end joint, so that, when ammonia vapor condenses to a liquid, it can flow under gravity to the receiver.

Receiver

This is a single vessel, which is used as a storage tank of the liquid ammonia, during the regeneration cycle, and it acts as an evaporator, during the absorption cycle. It is a thick steel pipe, 50 mm inner diameter, 60 mm outer diameter and 120 mm long. The axis of this pipe is inclined downward at about 40° to the horizontal. The lower end, is closed by a 10mm thick steel plate, and the upper end is closed by a hemisphere, 50 mm internal diameter and 10 mm thick, made of steel. A pressure gauge is fitted to the hemispherical end, which is also connected to the outlet end joint of the condenser coil through a control valve. The receiver is enclosed by a standard 4 inch galvanized pipe, having a length of 230 mm. This pipe acts as a tank to store cooling water for the receiver, during the regeneration cycle. This cooling water is then used as the water to be cooled by the evaporator during the absorption cycle.

Heating Unit

The heating unit uses electrical energy to provide the system with the required heat energy, which is equivalent to that, which can be obtained by a flat plate solar collector. This enables the apparatus to be tested inside a laboratory. Standard heating coil is used for the heating unit. The length of the heating coil used is adjusted so that, the heating power of the unit is about 0.2 kW. The heating unit is inclined at about 30° to the horizontal, the outlet end being uppermost. Hot water leaves the heating unit from the top edge and pass through the generator coil, which is immersed in the aqua-ammonia solution in the generator. The relatively cold water then leaves the generator coil, and enters the heating unit at the bottom edge, through an insulated standard half inch galvanized tube. Heating water circulates naturally, hot water, having a relatively lower density, rises upwards, whereas, relatively cold water, having higher density moves downwards. Standard ½" galvanized tubes are used for heating water tubing. Two sockets are provided, to allow a mercury thermometer to be used to measure the temperature of the hot water entering and leaving the generator. Four valves are also provided to control the flow of, either heating water, from the heating unit during the regeneration cycle, or cooling water, from the cooling water tank, during the absorption cycle. Heating unit and its connections are insulated to minimize heat loss to the surroundings.

Cooling Water Tank

This is a steel tank having a rectangular cross-section of width 0.38 m and length 0.45 m. The height of the tank is 0.6 m. This tank is insulated so that, cooling water can be stored at any desired absorption temperature. During the absorption cycle, cooling water is allowed to pass through the absorption coil, which is the same as the generator coil. A small pump is provided, which can be used to circulate cooling water from the tank, through the absorber, and back again to the tank, or to the drain as required.

Charging of the System

Ammonia is toxic and flammable, when mixed at certain ratios with air, so it is highly recommended to wear a face shield, or safety goggles during the charging process. Fittings, tubing, gauges and other connections must be of steel or aluminum. Use of copper or brass is prohibited. The system model is charged with a solution of ammonia, distilled water and a corrosion inhibitor. A solution cylinder is used to charge the system with the solution. A special cylinder was designed and constructed for this purpose, as shown in Fig. 2. A thick pipe of 100 mm inner diameter and 10 mm thick, is used to construct the cylinder. The length of this pipe is 375 mm and is closed by a base plate and a top plate, each has a thickness of 10 mm. Three fittings are provided in the top plate. These are used for a charging valve, purging valve and a pressure gauge connections. The charging valve is connected to a long tube, of inner diameter 16mm, which is fitted inside the solution cylinder and ends just above the base of the cylinder. The mass of the solution cylinder is found to be 16kg.

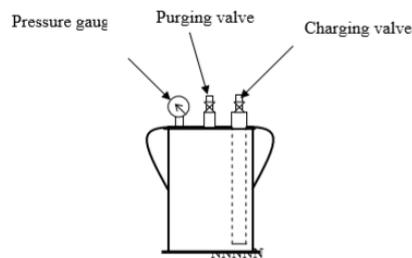


Fig. 2 Solution cylinder

The solution cylinder was filled as follows:

- 1- The pressure gauge was removed and a distilled water of 1.65 kg, and a corrosion inhibitor of about 40 g were put in the cylinder.
- 2- The pressure gauge was installed and the charging hose was connected to the solution cylinder, through the liquid valve.
- 3- A purging hose, was connected to the purging valve, the other end of the hose was immersed in water, contained in a bucket.
- 4- The solution cylinder was immersed in a cold water, which was contained in a bucket. This is necessary, because, when pure ammonia is absorbed by water, heat will be generated, the temperature, and hence the pressure, of the solution will increase, so, to ensure continuity of flow of ammonia gas, the generated heat must be removed continuously from the solution cylinder.
- 5- The valve of the charging cylinder, was opened gradually.
- 6- Vapor was purged from the solution cylinder, through the purging hose, frequently, to lower the pressure in the cylinder. This is necessary, so that, pure ammonia, can flow into the solution cylinder. Initially, air bubbles will come out of the solution cylinder. The water in the bucket will absorb the small quantity of ammonia purged. When air bubbles stop coming out from the solution cylinder,

this means that, only pure ammonia, exists inside the solution cylinder with water, and no further purge is required.

- 7- When the pressure in the solution cylinder was about 10 bar, the valve of the charging cylinder was closed, and the charging hose was disconnected. The solution cylinder was then removed from the cooling water.
- 8- The solution cylinder was then, put upside down, and connected to the system model, through the charging valve in the generator.
- 9- The charging valve of the system, and the valve of the solution cylinder were then opened. The aqua-ammonia solution charge was allowed to flow to the generator of the system. During this process, continuous cooling of the generator was carried out, to reduce the pressure in the generator, hence ensuring continuous flow of aqua ammonia from the solution cylinder to the generator. This continued until, all the charge was transferred from the solution cylinder to the generator of the system.
- 10- Additional charge of about 0.77 kg of distilled water, was added to the system. This resulted in a total mass of the distilled water to be about 2.25 kg.
- 11- Pure ammonia was then added to the system, through the charging valve in the generator, and air was purged out of the system through the evaporator valve, until air bubbles stopped coming out of the system. The final concentration of the aqua-ammonia solution in the system model, was about 41%, that is, about 2.42 kg of distilled water, and, about 1.68 kg, of pure ammonia.

3. Test Procedure

To be able to find out the effects of the condenser temperature, on the performance of solar absorption refrigeration systems, three tests were carried out, at average condenser temperatures of, about 25, 20 and 15°C. The test procedure was as follows:

- 1- Valves 1 and 2, of the heating water circuit, and valves 3 and 4, of the cooling water circuit, shown in Fig. 1, were opened. This allowed tap water, to flow from the main supply, through the tank, to the system, through the heating unit, generator/absorber coil and then out of the system to the drain.
- 2- Valves 3 and 4, were then closed and valve 5 was opened to make sure that, no air was trapped in the heating water circuit. Valve 5 was then closed, and the heating water circuit, including the tank of the heating unit, was full of water.
- 3- Cooling water was supplied to the condenser cooling water tank.
- 4- Initial readings of the generator pressure, inlet and outlet heating water temperatures, condenser cooling water temperature and the ambient temperature, were recorded, and the heating unit was switched on.
- 5- The quantities mentioned in step 4, above, were recorded every half an hour, throughout the regeneration cycle.

6- The heating unit was switched off, when the rise in temperature of the outlet heating water, became very small. This was the end of the regeneration cycle.

7- Valves 1&2 of the heating unit were closed, and valves 3&4, of the absorber cooling water, were opened.

8- The absorber valve A, was closed, and ammonia vapor, which was trapped in the condenser coil, was allowed to condense and flow down to the receiver.

9- Valve B of the receiver was then closed.

10-When the absorber temperature was reduced to about 20°C, initial readings for the absorption cycle were recorded. These included, absorber pressure, evaporator pressure, inlet and outlet cooling water temperature, evaporator temperature and the ambient temperature.

11-Valve A, of the absorber, and valve B, of the receiver, were then, slightly opened, and the quantities mentioned in step 10 above, were recorded every half an hour, throughout the absorption cycle.

4. Results and Discussion

The results of the test during the regeneration, and absorption cycles, for the three different condenser temperature, are shown in the following tables:

Test No.1: Condenser Temperature = 25°C

Table 1a the Regeneration Cycle

Time	Generator pressure (bar)	Heating water temperature (°C)		Condenser cooling water temperature(°C)	Ambient temperature (°C)
		in	out		
9:00	2.3	30	30	18	32
9:30	3.9	56	38	18	32
10:00	6.0	72	48	18	32
10:30	7.2	81	52	18	33
11:00	8.3	89	56	18	33
11:30	9.0	91	61	18.5	32
12:00	9.7	93	65	18.5	32
12:30	10.5	94	70	18.5	33
13:00	11.2	95	75	19	33
13:30	11.7	96	78	20	33
14:00	12.0	96	80	21	34
14:30	12.2	96	84	22.5	35
15:00	12.3	96	86	24	35
15:30	12.4	97	88	26	34
16:00	12.5	97	89	27	34

Table 1b the Absorption Cycle

Time	Absorber press.(bar)	Evaporator press.(bar)	Cooling water Temp.(°C)		Evaporat or Temp.(°C)	Ambient Temp.(°C)
			in	out		
9:00	1.4	10.7	20	22	30	33
9:30	1.6	5.1	20	22	20	33

11:00	1.4	1.4	22	23	12	33
10:30	1.22	5.1	21	22	12	34
10:00	1.2	3.2	21	22	18	33

Test No.2: Condenser Temperature = 20°C

Table 2a the Regeneration Cycle

Time	Generator pressure (bar)	Heating water temperature (°C)		Condenser cooling water temperature (°C)	Ambient Temperature (°C)
		in	out		
10:00	2.3	30	30	16	33
10:30	3.3	50	35	16	33
11:00	5.0	68	42	16	33
11:30	5.9	74	49	16	34
12:00	7.0	79	55	16	33
12:30	8.1	84	58	16.5	34
13:00	8.8	89	61	17	34
13:30	9.4	91	64	18	34
14:00	9.9	93	67	20	35
14:30	10.1	94	71	21	35
15:00	10.3	95	73	22	35
15:30	10.4	95	75	23	34
16:00	10.5	96	76	24	35

Table 2b the Absorption Cycle

Time	Absorber press. (bar)	Evaporator press. (bar)	Cooling water temp. (°C)		Evaporator temp. (°C)	Ambient temp. (°C)
			in	out		
9:00	1.4	10.0	20	22	30	32
9:30	1.5	5.25	20	22	20	32
10:00	1.55	3.0	20	21	18	33
10:30	1.55	2.25	21	22	17	32
11:00	1.6	1.6	21	22	16	33

Test No.3: Condenser Temperature = 15°C

Table 3a the Regeneration Cycle

Time	Generator Pressure (bar)	Heating water temperature (°C)		Condenser cooling water Temperature (°C)	Ambient Temperature (°C)
		in	out		
9:00	2.3	30	30	11	32
9:30	3.2	47	35	11	32
10:00	4.9	66	42	11	32
10:30	5.6	72	46	11	33
11:00	6.5	78	52	11	33
11:30	7.4	82	57	11.5	32
12:00	8.2	85	61	12	33
12:30	8.6	88	65	14	33
13:00	9.0	90	68	16	33
13:30	9.3	91	70	17	33
14:00	9.4	93	71	18	34

Table 3b the Absorption Cycle

Time	Absorber Pressure (bar)	Evaporator Pressure (bar)	Cooling water Temperature(°C)		Evaporator Temperature (°C)	Ambient Temperature (°C)
			in	out		
9:00	1.5	10.25	20	22	30	32
9:30	1.65	4.5	20	22	19	33
10:00	1.7	3.0	21	22	17	32
10:30	1.65	2.25	21	22	16	32
11:00	1.7	1.7	22	23	15	33

Table 4 Results of the Simulation Program for an Average Condenser Temperature of about 25°C

a- The Regeneration Cycle

Time	solar energy (kJ)	sol. temp. (°C)	sol. press. (bar)	sol. conc. (%)	vapour conc. (%)	sol. mass (kg)	vapour mass (kg)	mass of vapour (kg)	net vapour (kg)	water content (kg)
9:00	-	30.0	2.30	41.0	-	4.100	-	-	-	-
10:00	227.273	41.5	3.23	41.0	-	4.100	-	-	-	-
11:00	290.397	52.2	4.64	41.0	-	4.100	-	-	-	-
12:00	333.362	63.6	6.52	41.0	-	4.100	-	-	-	-
13:00	351.566	74.5	8.82	41.0	-	4.100	-	-	-	-
13:55	188.086	80.0	10.10	41.0	-	4.100	-	-	-	-
14:00	152.718	80.8	10.10	40.4	96.7	4.057	0.043	0.043	0.043	0.001
15:00	303.191	82.7	10.10	39.3	96.4	3.976	0.081	0.124	0.124	0.004

b-The Absorption Cycle

time	evaporator temperature (°C)	absorber pressure (bar)
9:00	30.0	1.300
10:00	19.8	1.535
11:00	9.4	1.654

The coefficient of performance is 0.062

Table 5 Results of the Simulation Program for an Average Condenser Temperature of about 20°C

a- The regeneration Cycle

Time	solar energy (kJ)	sol. temp. (°C)	sol. press. (bar)	sol. conc. (%)	vapour conc. (%)	sol. mass (kg)	vapour mass (kg)	net mass vapour (kg)	of water content (kg)
9:00	-	30.0	2.30	41.0	-	4.100	-	-	-
10:00	227.273	41.5	3.23	41.0	-	4.100	-	-	-
11:00	290.397	52.2	4.64	41.0	-	4.100	-	-	-
12:00	333.362	63.6	6.52	41.0	-	4.100	-	-	-
13:00	351.566	74.0	8.57	41.0	-	4.100	-	-	-
14:00	340.804	76.6	8.57	39.5	96.7	3.994	0.106	0.106	0.003
1500	303.191	78.6	8.57	38.2	96.3	3.906	0.088	0.194	0.007

Total solar energy received is: 1846.593 kJ

Total mass of pure ammonia generated is: 0.187 kg

b-The Absorption Cycle

time	evaporator temperature (°C)	absorber pressure (bar)
9:00	30.0	1.300
10:00	18.7	1.521
11:00	7.1	1.655

The coefficient of performance is 0.078

Table 6 Results of the Simulation Program for an average
Condenser Temperature of about 15°C

a- The Regeneration Cycle

Time	solar energy (kJ)	sol. temp. (°C)	sol. press. (bar)	sol. conc. (%)	vapour conc. (%)	sol. mass (kg)	vapour mass (kg)	net mass vapour (kg)	of water content (kg)
9:00	-	30.0	2.30	41.0	-	4.100	-	-	-
10:00	227.273	41.5	3.23	41.0	-	4.100	-	-	-
11:00	290.397	52.2	4.64	41.0	-	4.100	-	-	-
12:00	333.362	63.6	6.52	41.0	-	4.100	-	-	-
12:29	101.813	67.0	7.40	41.0	-	4.100	-	-	-
13:00	249.753	70.4	7.40	39.8	97.3	4.013	0.087	0.087	0.002
14:00	340.804	73.4	7.40	38.2	96.8	3.905	0.109	0.195	0.006

Total solar energy received is: 1543.402 kJ

Total mass of pure ammonia generated is: 0.190 kg

b- The Absorption Cycle

time	evaporator temperature (° C)	absorber pressure (bar)
9:00	30.0	1.300
10:00	18.6	1.519
11:00	6.9	1.654

The coefficient of performance is 0.094

From the above tables, and the enthalpy-concentration chart for aqua- ammonia solution, the average temperature of the inlet and outlet water, from the generator/absorber, is used to find the concentration of the aqua-ammonia solution, at the corresponding pressure. This result is shown in Tables 1, 2 and 3, for test no.1, test no.2 and test no.3, respectively. Tables 4, 5 and 6 shows theoretical results, for the three cases of condenser temperatures, of, 25, 20 and 15°C respectively, as obtained from the simulation program. The experimental results shown in the above tables, are plotted, together with the theoretical analysis, as shown in Figs. 3 to 8. The cycle 1-2-3-4-5, is the theoretical cycle, and the cycle 1-6-7-8-9-1, is the actual one. Initially, the

aqua-ammonia solution, was at state (1), which corresponds to a concentration of 41%, a temperature of 30°C and a pressure of 2.3 bar. When the heating unit was switched on, the temperature and the pressure of the solution had increased until the saturation pressure, corresponding to the condenser temperature, is reached. Before the saturation pressure was reached, the whole quantity of heat, which is supplied to the generator, was used to raise the solution temperature, no ammonia vapor was generated, and the concentration of the solution, remained constant at 41%. After the saturation pressure had reached, ammonia vapor started to rise up from the solution, at constant pressure, the concentration started to decrease and the temperature continued to increase. When the increase in temperature became very small, the heating unit was switched off, and this was the end of the regeneration cycle. At this point, the generator valve was closed and cooling water was allowed to flow through the weak aqua-ammonia solution in the absorber, the temperature and pressure of the solution started to decrease at constant concentration. After that, the receiver valve was closed, and cooling of the absorber was continued. When the aqua-ammonia solution was cooled down, to the required absorption temperature of about 20°C, the absorber valve and the evaporator valve were slightly opened, and the ammonia liquid started to vaporize in the evaporator, and hence produce cooling effect there, and flow back, to be absorbed by the weak solution in the absorber. The concentration of the solution started to increase, the temperature was kept constant, due to continuous cooling of the absorber. The pressure of the solution in the absorber started to increase, because the solution was becoming strong. This process continued until the pressure in the evaporator, became equal to the pressure in the absorber, and all ammonia liquid in the receiver, was evaporated, and absorbed by the aqua-ammonia solution in the absorber. At the final state the solution had a pressure of about 1.7 bar a temperature of about 20°C and a concentration of about 41%. The mass of the water to be cooled in the evaporator, for the three tests, was, $m = 1.5$ kg.

Table 7 Results of Test No.1, (Condenser Temperature = 25°C)

P(bar)	2.3	6.0	8.3	9.7	11.2	12.0	12.3	12.5	1.4	1.6	1.7
T(°C)	30	60	72	79	85	88	91	93	21	21.5	22.5
x(%)	41	40.9	40.8	40.7	40.5	40	39.2	38.8	39.2	40	41

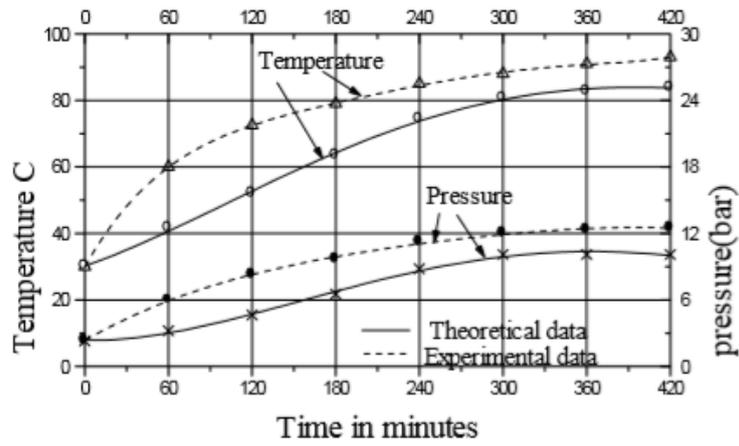


Fig. 3 Variation of Temperature and Pressure with Time, for Test No.1

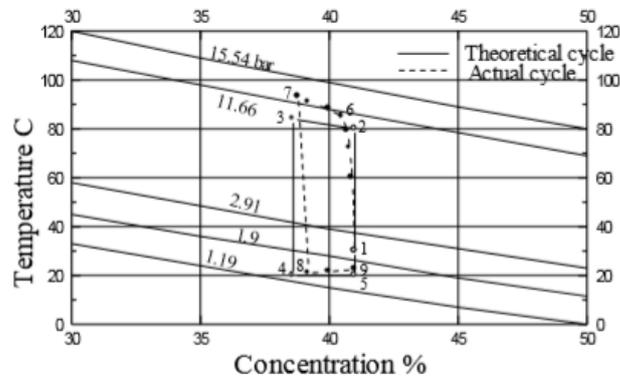


Fig. 4 Actual and Theoretical Cycles for Test No.1 (Condenser Temperature = 25 C)

Table 8 Results of Test No.2, (Condenser Temperature = 20°C)

P(bar)	2.3	5.0	7.0	8.8	9.9	10.3	10.5	1.4	1.55	1.6
T(°C)	30	55	67	75	80	84	86	21	20.5	21.5
x (%)	41	40.8	40.7	40.6	40.5	39.8	38.6	39.0	40.0	41.0

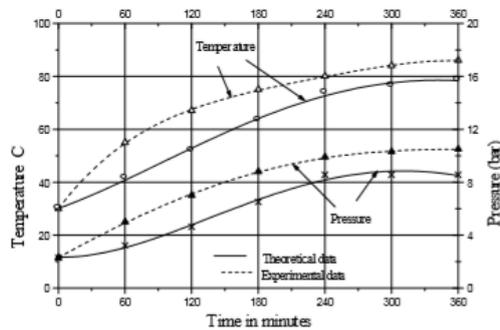


Fig. 5 Variation of Temperature and Pressure with Time, for Test No.2

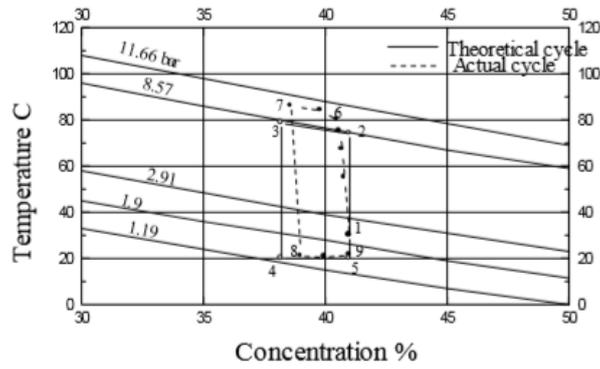


Fig. 6 Actual and Theoretical Cycle for Test No.2 (Condenser Temperature = 20 C)

Table 9 Results of Test No.3, (Condenser Temperature = 15°C)

P(bar)	2.3	4.9	6.5	8.2	9.0	9.5	1.5	1.65	1.7
T(°C)	30	54	65	73	79	82	21	21.5	22.5
x (%)	41	40.8	40.6	40.3	39.5	38.7	39.1	40	41

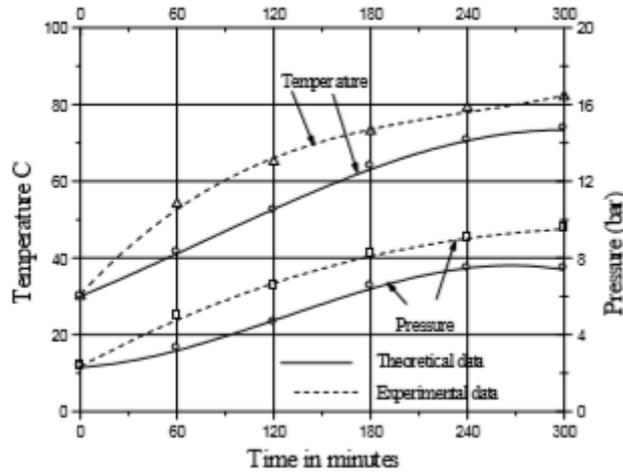


Fig. 7 Variation of Temperature and Pressure with Time, for Test No.3

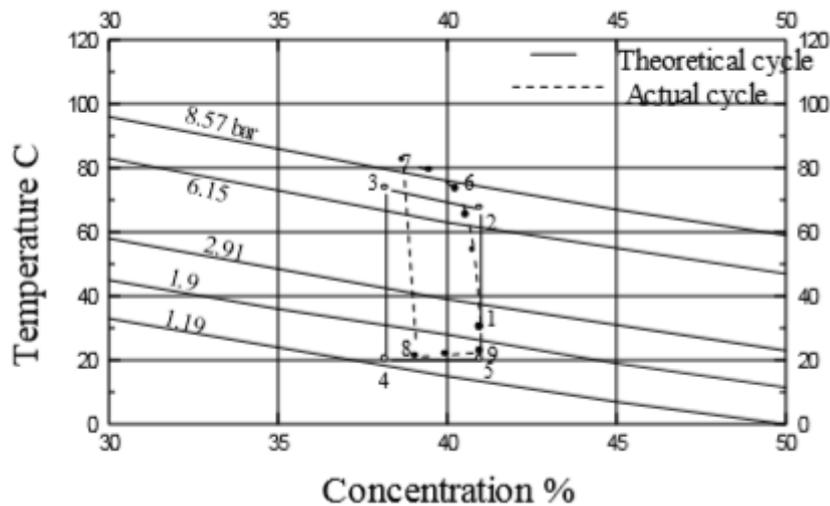


Fig. 8 Actual and Theoretical Cycle for Test No.3 (Condenser Temperature = 15 C)

Let ΔT_e to be the reduction in temperature of the water in the evaporator, hence, the cooling effect is given by:

$$Q_e = m c_p \Delta T_e \quad (1)$$

Where, c_p is the specific heat of water. The rate of heating of the heating unit, was about 0.2 kW, so that the total energy supplied, during the regeneration cycle, was about:

$$Q_{in} = 0.2 \times t_g \times m \times 3600 \text{ KJ} \quad (2)$$

Where, t_g , is the period of the regeneration cycle in hours. Therefore, the coefficient of performance (COP), of the system is given by the relation:

$$(COP)_{exp} = \frac{Q_e}{Q_{in}} \quad (3)$$

Table 10 Summary of Test Results

Test number		1	2	3
Regeneration cycle	Duration (hours)	7	6	5
	Condenser cooling water temperature(°C)	18-27	16-24	11-18
	Maximum solution temperature (°C)	93	86	82
	Maximum solution pressure (bar)	12.5	10.5	9.4
Absorption cycle	Duration (hours)	2	2	2
	Absorber cooling water temperature (°C)	16-23	17-22	17-23
	Minimum evaporator temperature (°C)	15	16	15
	Actual coefficient of performance	0.019	0.02	0.026
	Theoretical coefficient of performance	0.062	0.078	0.094

It is known that, the coefficient of performance of an absorption cycle, is, generally, poor, [2]. Comparing the results of the three tests, it is clear that, the coefficient of performance increases, as the condenser temperature decreases. This apparently means that, it is better for solar absorption refrigeration systems, to work at a lower condenser temperature, but, this may not be true. The following discussion clarifies this point: The coefficient of performance of a refrigeration system, in general, is a measure of the ability of the system, to make use of the input energy, to produce cooling effect, and therefore, it is an indication of the operating cost of the system. In solar refrigeration, the input energy is free, and the design of a solar refrigeration system, is concerned with obtaining minimum cost cooling effect. Thus, it may be desirable to design a system with a lower coefficient of performance, if the cost is significantly reduced, [1].

Referring back, to the test results, it is clear that, to obtain a high coefficient of performance for an absorption refrigeration system, then, a condenser cooling water, at a very low temperature, must be provided. This makes additional cost to the system. On the other hand, if tap water is used as a condenser cooling water, then, the coefficient of performance is expected to be very low, but the overall cost of the system, would be at its minimum.

Swartman and Swami Nathan, [12], experimentally studied the operation of an intermittent absorption refrigeration system, using aqua ammonia solution, and operated by a flat plate collector. In their experiment, the coefficient of performance, was found to be about 0.06, [1]. In the Swartman system the, absorber and the generator were separate vessels. In addition, the aqua-ammonia solution, itself, was circulating through the solar collector tubes, and was heated there, i.e., the solar collector, was part of the system generator. In this research, water is heated in a heating unit, which is equivalent, to a flat plate collector, the hot water is then used to heat the aqua-ammonia solution in the generator of the system. In addition, there is a single vessel performing both functions of the generator, and the absorber. The main advantage of this design over Swartman one, is that, the pressure in the solar collector, is low, and there is no need to use special tubing and connections, to withstand high pressures of the generator, hence, standard water tubes, fittings and valves can be used in the solar collector. This has the effect of reducing the overall cost of the system, in addition, it facilitates the construction and control of manufacture of the flat plate collector. Swartman design, on the other hand, has the advantage that, all solar energy collected by the solar collector, is used to heat the aqua-ammonia solution, whereas in this research, only part of the solar energy, collected by the solar collector, is used to heat the aqua ammonia solution in the generator of the system, the other part, being losses to the surroundings. This explains why the coefficient of performance obtained in this research, is less than that, obtained in Swartman and Swami Nathan's experiment. The actual cycles shown in Figs. 4, 6 and 8, follow similar routes to the corresponding theoretical cycles. The difference between the experimental and the theoretical results, arise from different factors as stated below:

- 1- The heating unit of the apparatus, is assumed to be identical to the flat plate collector, which is used in the theoretical analysis. This is not the case, from the point of view of the quantity of heat generated. The heating unit gives a constant rate of heating, throughout the test, whereas, in the flat plate collector, the quantity of heat varies from one hour to another.
- 2- For heat energy to flow from one place to another, there must be carried out in this research, the temperature of the aqua-ammonia solution in the generator/absorber, is assumed to be the same as the temperature of the circulating water, which is taken as the average of the inlet and outlet water temperatures.
- 3- The temperature of the condensed ammonia in the condenser, is assumed to be the same as the temperature of the cooling water, in the condenser tank.
- 4- During the regeneration cycle, the generated ammonia vapor, passes through a vertical tube to the condenser. This vertical tube was made long, and it was assumed that, any water vapor rises with ammonia vapor, condenses inside this tube, and returns back, by gravity, to the generator, leaving only pure ammonia to flow to the condenser.

- 5- In the experiment carried out, it was assumed that, the absorption temperature was constant during the absorption cycle, which may not be true, because of the variation of the quantity of heat rejected due to the absorption process.
- 6- During the test, temperatures were measured by an ordinary mercury thermometer, which may give inaccurate readings.

VI. CONCLUSIONS AND RECOMMENDATIONS

1. Conclusions

In this study, a computer simulation program was written, using the FORTRAN language, to predict theoretical performance of an intermittent absorption refrigeration system. The program was run for different values of performance parameters, and gave good results. The program was able to calculate the properties of the fluids encountered in the experiment, and give values for different required quantities, such as; the quantity of the cooling water required for the absorber, the required tube length in the generator/absorber unit, the quantity of the cooling water required in the condenser tank, the required length of the condenser coil,...etc., and finally, the program gives the value of the theoretical coefficient of performance of the system, according to the given input data. A simple intermittent ammonia absorption refrigeration system was designed and constructed in this study. The system was designed so that, there is a single vessel, performing both functions of the generator, and the absorber, and, another single vessel, performing both functions of the receiver and the evaporator, alternatively. The system consists of the following main components: the generator/absorber unit, the condenser and the receiver/evaporator unit. All the system components were designed so as to ensure simplicity, and ease of construction and operation of the system. They are fabricated from steel plates, angle sections, channel sections and tubes. Two pressure gauges were included to indicate the pressure in the generator/absorber and in the receiver/evaporator units. The system components were properly assembled, and successfully tested, for functioning, up to a pressure of 15 bar. They showed a very good performance, each component performed its function as required, and no leakage was noted during the test.

The system was tested for three different values of condenser temperature, these are 25, 20 and 15°C. The test results showed that the coefficient of performance of an intermittent absorption refrigeration system is high when the condenser temperature is low. The value of the actual coefficient of performance, which is obtained from the test, is lower than the theoretical value, which is obtained from the computer program. The difference between the two values is, largely, due to inaccuracy in measurements, which were taken during the experiment. The use of data logger, and advanced measuring techniques, are recommended for future work.

It can be concluded that, the apparatus, which has been designed, constructed and tested in this research, can be used successfully, to test the performance of a solar absorption refrigeration system, which uses aqua-ammonia solution in an intermittent cycle. The apparatus can work safely, at a pressure of 15 bar. This pressure corresponds to a condenser temperature of about 30°C, It is clear that, only slight cooling, of the condenser cooling water, is required and, in some instances, tap water, which is taken directly from the main supply, can be used as a condenser cooling water. The apparatus is also characterized by the use of an electrical heating unit, to act as a solar collector. This enables the apparatus to be located inside a laboratory, instead of outdoors under the sun light, and greatly simplifies execution of the experimental work, which can be carried out at any time throughout a day. This advantage becomes clear, if it is mentioned that, some experiments may take up to 24 hours duration.

2. Recommendations

There are many parameters, which affect the performance of a solar absorption refrigeration system. The apparatus which has been designed and constructed in this research, can be used by research students, to study the effect of variation of such parameters on the performance of solar absorption refrigeration systems. The following are some recommended areas, which can be studied in the future, by research students, using this apparatus to see their effect on the performance of a solar absorption refrigeration system:

- 1- Absorber cooling water temperature.
- 2- Concentration of ammonia in the aqua-ammonia solution.
- 3- Condensing temperature.
- 4- The quantity of the aqua-ammonia solution, in the system.
- 5- Variation of solar energy collected, by a flat plate collector.
- 6- Use of a heat exchanger, in the generator of the system.

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