Design of Solar Powered Vapour Absorption System

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***Abstract*— Over the past few decades, energy is the backbone of technology and economic development. In addition to men, machines and money, 'energy' is now the fourth factor of production. The objective of this paper is to design and study an environment friendly vapour absorption refrigeration system of unit capacity using R 717 (NH3) and water as the working fluids. The system is designed and tested for various operating conditions using hot water as heat source. In this paper, performance of the fabricated system is outlined with respect to various operating conditions related to heat source, condenser, absorber and evaporator temperatures. The basic idea of this paper is derived from the solar heating panel installed on the hostel roofs of the institute. The unit has been installed for about an investment of Rs. 1 crore 70 lacs. But the irony is that, this solar heating unit remains idle in the summer months. Also the solar potential is at maximum in the summer.**

***Index Terms*—Vapour Absorption, solar heating, environment**

I. INTRODUCTION

SOLAR energy is a very large, inexhaustible source of energy. The power from the sun intercepted by the earth is approximately 1.8 ×1011 MW which is much more larger than the present consumption rate on the earth of all commercial energy sources. Thus, in principle, solar energy could supply all the present and future energy needs of the world on the continuing basis. This makes it one of the most promising of the unconventional energy sources. In addition to its size, solar energy has two other factors in its favour. First unlike fossil fuels and nuclear power, it is an environmental clean source of energy. Second, it is free and available in adequate quantities in almost all parts of the world where people live. However, there are many problems associated with its use. The main problem is that it is a dilute source of energy.

Even in the hottest regions on earth, the solar radiation flux rarely exceeds 1kWh/m2 and the total radiation over a day is best about 6 kWh/m2.These are low values from the point of view of technological utilization. Consequently, large collecting areas are required in many applications and this result in excessive costs.

A second problem associated with the use of solar energy is that its availability varies widely with time. The variation in availability occurs daily because of the day-night cycle and also seasonally because of the earth's orbit around the sun. In addition, variation occurs at a specific location because of local weather conditions. Consequently, the energy collected when the sun is shining must be stored for use during periods when it is not available. The need for storage significantly adds to the cost of the system. Thus, the real challenge in utilizing solar energy as an energy alternative is to address these challenges. One has to strive for the development of cheaper methods of collection and storage so that the large initial investments required at present in most applications are reduced.

Flat plate collectors

Flat plate collector is an insulated weather proofed box containing a dark absorber plate under one or more transparent or translucent covers.

Fig. 1 Solar water heater

Parts of a Flat Plate Collector:

Cover Plate: It is made up of glass tempered with a low iron content and 3.2-6.4 mm thick. The collector has 85% transmittance when this type of glass is used.

Absorber Plate: It is made up of copper because of its high conductivity. Moreover, it is corrosion resistant. these copper plates 0.05 mm thick with 1.25 cm tubes. Tubes are spaced 15 cm apart, the efficiency is 97 %.. Moreover, black paint over copper plate is used which has absorptance =0.85-0.9 and emmitance=0.08-0.12.

Enclosure/Insulation: It is made up of steel, aluminium or fibre glass. Fibre glass is widely used.

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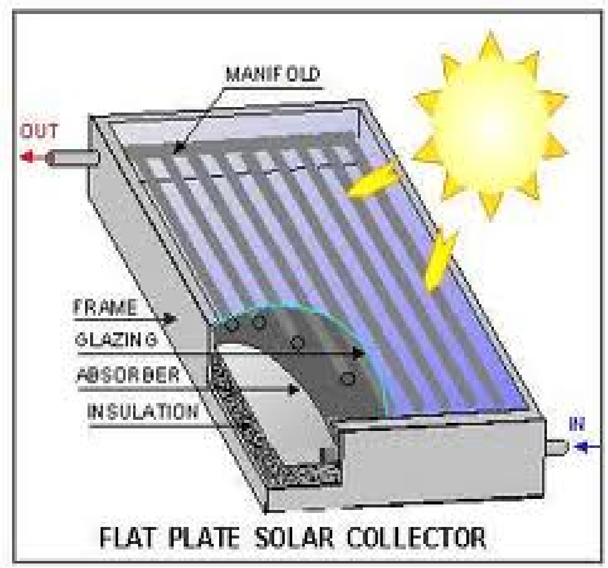

Fig. 2 Flat plate collector parts

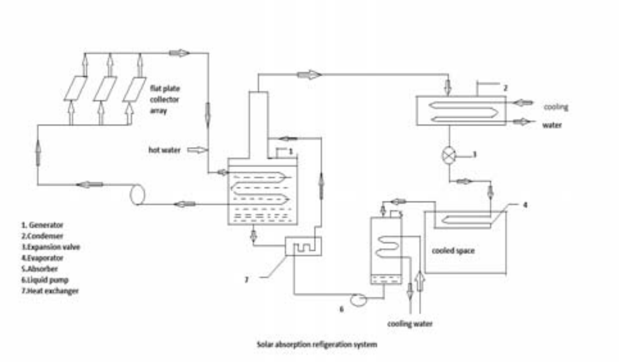

Fig. 3 Design layout of a solar absorption refrigeration system

II. MATHEMATICAL MODELING

The operating pressures at which the system is working needs to be determined to carry on further calculations, using an enthalpy concentration chart. Once the pressure of the condenser (Pc) and the pressure of the evaporator (Pe) are determined the corresponding points can be fixed on the chart as shown in fig. 4. The various other points and condition lines for components like absorber, generator, heat exchangers etc can be subsequently fixed.

A. Condenser Pressure (Pc)

The pressure to be maintained in the condenser for changing the phase of ammonia vapours into ammonia liquid depends on type of condensing medium used and its temperature.

In this system, water is used as a condensing medium. Water is available at a temperature of 25 0C. i.e. condensing temperature is Tc= 25 0C.

For condensing ammonia vapours at 250C, the corresponding pressure required can be noted from the refrigeration table of ammonia (R-717).

In this way, the condenser pressure is fixed at Pc=10 bar.

B. Evaporator pressure (Pe)

The evaporator pressure can be fixed according to the minimum temperature required to be maintained in the evaporator chamber. The minimum temperature attained is not a designing criterion in this system, as we require to cool water only for drinking purposes. The pressure maintained in the evaporator should be as close to the atmospheric pressure as possible, because maintaining a higher pressure is a difficult and costly affair. Moreover it also has leakage problems and the unit needs to be hermetically sealed. The evaporator pressure is kept equal to the atmospheric pressure(1 bar) , to ensure design economy.

The corresponding saturation temperature in the evaporator (ammonia vapours) becomes -33 0C.

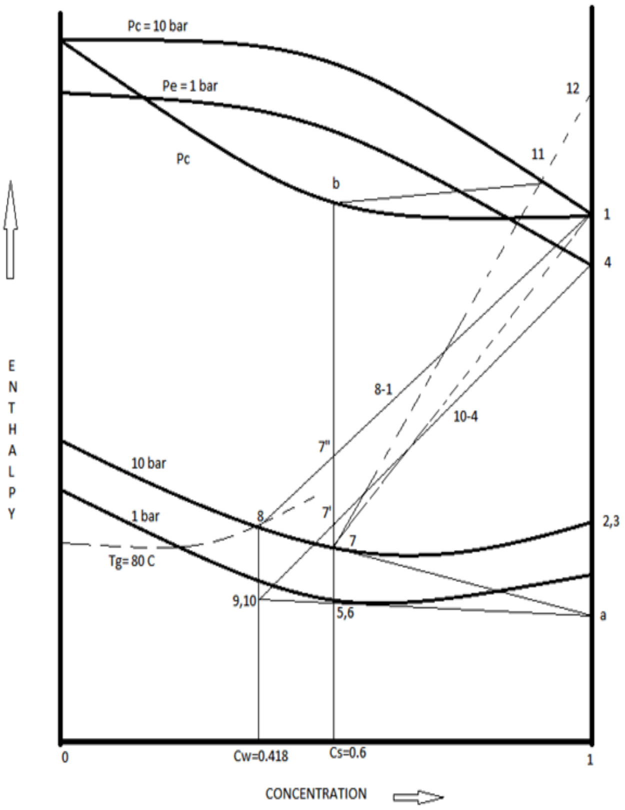

Fig. 4 Enthalpy-concentration diagram

Now the points of condenser pressure and evaporator pressure can be plotted on the pressure enthalpy chart as points 1, 2, 3 and 4.

Point 1 represents pure NH3 saturated vapour at condenser pressure Pc and concentration C=1.

Point 2 represents pure NH3 saturated liquid at Pc and C=1. This point is marked in liquid region.

Point 3 represents the condition of pure NH3 (wet) but at pressure Pe and C=1. Point 2 coincides with point 3 as 2-3 is a throttling process in which enthalpy remains contant.

Point 4 represents the condition of pure NH3 at pressure Pe these are saturated vapours which absorbs heat in evaporator and converts from wet vapour to saturated vapour. This point is marked in vapour region.

The enthalpies at points 1, 2, 3 and 4 can be noted from the chart.

h1= 1630 KJ/Kg
h2= h3= 460 KJ/Kg
h4= 1530 KJ/Kg

Now, let as assume the refrigeration capacity of the unit to be 1TR.

1. The refrigerating effect produced or the heat absorbed by ammonia refrigerant in the evaporator is Qe= h4 – h3 KJ/Kg of ammonia
Say the mass flow rate of ammonia in the evaporator be Mr. Therefore,

Mr × (h4 – h3) = 1 TR
Mr × (h4 – h3) = 210 KJ/min
Therefore, Mr × (1630 - 460) = 210
It gives Mr = 0.18 Kg/min

Thus the mass flow rate of the ammonia through the evaporator ie

$$\boxed{M_r = 0.18 \text{ Kg/min}}$$

2. Now, the temp. of the water going inside the generator is more than 800C (about 84 0C) . That is, taking the temp. in the generator Tg = 80 0C (assuming losses)
Thus the point 8 can be marked on the pressure enthalpy chart where the constant temp line of 80 0C intersects the pressure line of 10 bar.
Point 8 represents the hot weak liquid having concentration Cw inside the generator.
Thus the corresponding concentration of the weak solution can be directly noted down from the chart as Cw = 0.418
After fixing the point 8, the point 5 can also fixed,
Point 5 represents the strong aqua coming out of the absorber after absorbing the vapours coming out of the evaporator. The concentration of the strong solution, say C5, can be determined by knowing the degasifying factor.

The degasifying factor is the amount of NH3 vapours removed from the strong solution in the generator. Higher value of this factor is desirable because its higher value prevents water from being evaporated, which creates trouble, and is necessary to be removed before entering into condenser.

Here in this system, a mass of 0.18 Kg/min is required to be flown across the evaporator for steady state. Thus the degasifying factor becomes 0.18

Thus the concentration of strong aqua solution becomes
C5= Cw + 0.18
i.e., C5= .418 + .18 = 0.596
Thus taking the concentration of strong solution to be

$$\boxed{C_s = C_5 = 0.6}$$

Hence now we know the concentration and pressure at point 5, thus point 5 can be located on the chart at C5= 0.6 and pressure Pc = 10 bar.
Point 6: This is the condition of the aqua solution whose concentration C5 = 0.6, but the pressure is increased from Pe to Pc as it passes through the pump. Point 6 coincides with point 5 on the C-h chart as enthalpy does not change when the aqua pressure increase passing through the pump.
Point 7: As the strong low temperature aqua solution passes through heat exchanger it gains the heat and its enthalpy increases, but its concentration Cs remains same as well as pressure remains same as Pc. Now the point 7 can be marked on the C-h diagram as pressure at 7 and C7 are known.

Now join points 8 and 7 and extend till it cuts the Y axis (enthalpy) at ‘a’ as shown in figure, then join point ‘a’ and 5 and extend till it cuts the vertical line passing through 8. This also decides the position of point 9 and 10.
Point 9: This shows the condition of weak liquid coming out of the heat exchanger after giving heat to the strong solution. So enthalpy is reduced. Subtracting the heat lost by the weak solution in heat exchanger, point 9 can be marked as the concentration does not change.
Point 10: The point 10 represents the same enthalpy as 9 but at reduced pressure Pe as it passes through the pressure reducing valve.

Absorber

In absorber, the pure NH3 gas enters at condition 4 and weak aqua solution enters at condition 10 and after mixing, strong aqua comes out at condition 5. The mixing occurring inside is underlined but aqua condition coming out is definitely known. Join the points 10 and 4 and extend the vertical line passing through point 7 till it cuts at point 7". Now we can say that mixing taking place along the line 4-10 and at pressure Pe and resulting aqua is coming out at 5 after losing heat in the absorber. Joining the points 4 and 10 and marking point 7" is not necessary for solving the problems or designing the system components.

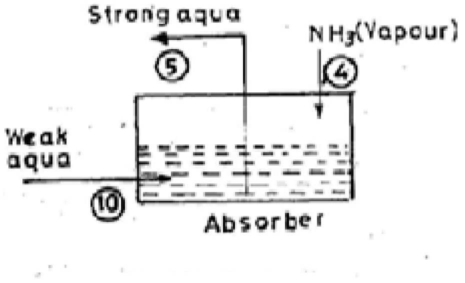

Fig. 5 Absorber

Generator

In generator, strong aqua is heated by supplying heat Qg,. The strong aqua enters into the generator at condition 7 and pure NH3 vapour comes out at condition 1 and weak aqua at condition 8. Now join the points 8 and 1 and extend the vertical line through point 7 to mark the point 7" which cuts the line 1-8. Now, we can say that the separation is taking place along the line 1-8 and at pressure pc. Joining the points 1 and 8 marking the point 7" is not necessary for solving the problems or designing the system components.

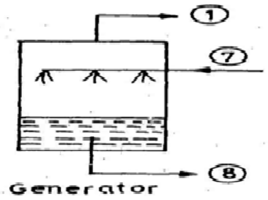

Fig. 6 Generator

III. CALCULATIONS:

a. Mass flow rate of ammonia as refrigerant
Mr = 0.18 Kg/min

b. Heat removed in the evaporator
= refrigeration effect
= Mr. × (h4 – h3)
= 1 TR = 210 KJ/min
If cold water flow rate is Mw then
Mw Cp ΔT= 210 Kj/min, if ΔT=17 0C
then Mw= 3.0 Kg/min

c. Heat removed in condenser
Heat removed in the condenser by the circulated cooling water is given by the equation:
Qc = (h4-h3) per kg of ammonia
i.e. Qc = Mr × (h2 – h1)
= 0.18 × (1630 - 460)
Therefore, heat removed
Qc = 211.6 KJ/min

d. Heat removed from absorber.
When the NH3 vapour at point 4 and aqua at 10 are mixed, the resulting condition of the mixture in the absorber is represented by 7” and after losing the heat in the absorber (as it is cooled), the aqua comes out at condition 5. Therefore, the heat removed in the absorber is given by
Qa = (h7” – h5) per Kg of aqua.

Extend the triangle 10-7”-5 towards right till 10-7” cuts at 4 and 10-5 cuts at point ‘a’ on x axis. Therefore, heat removed per kg of NH3 is given by
Qa = (h4 - ha) per kg of ammonia
Qa = Mr × (h4 - ha)
= 0.18 × (1550 - 70)
= 266.4 KJ/ min
Thus Qa = 266.4 KJ/min

Now the resultant aqua is at condition 7”, which looses heat up to condition 5.
Temp at 7” = i.e. T7” = 82 0C (from C-h chart)
Say, water gets heated to a temp of 82 C from 25 0C while removing heat from the absorber.
If Mw = mass of cooling water required
Then
Mw × Cp × (Ti – T0) = 266.4
Mw × 4.18 × (82 - 25) = 266.4
Mw = 1.12 Kg/min
That is, the mass of cooling water required in absorber is 1.12 kg/min.

e. Heat given in the generator
Say Qg is the heat supplied in the generator and Qd is the heat removed from water vapour then the net heat removed per kg of aqua is given by
qg – qd = (h7’ – h7) per kg of aqua
as the aqua goes out in at condition 7 and comes out at condition 8 and 1, which can be considered as a combined condition 7’.
By extending the triangle 8-7-7’ towards right till 8-7’ cuts at 1 and 8-7 cuts at a on y axis, then the heat removed per kg of NH3 is given by
Qg - Qd = (h1 – ha) per kg of ammonia
Now for finding out Qd separately, extend the vertical line 7-7’ till it cuts the auxiliary line Pc and mark point ‘b’ as shown. Then draw a horizontal line through b which cuts Pc line in vapour region at point 11. Then join the points 7 and 11 and extend the line till it cuts y axis at 12.
Then Qd is given by Qd = (h12 – h1) per kg of ammonia
Qd = 0.18 × (1760 - 630)
Qd = 23.4 KJ/min

now using equation Qg – Qd = (h1 - ha) we have
Qg - 23.4 = 0.18 × (1630 - 70)
T therefore, Qg = 304.2 KJ/min

Thus the amount of heat required in the generator for running this unit is

$$\boxed{Q_g = 304.2 \text{ KJ/min}}$$

Now this amount of heat is provided by the hot water coming out of solar flat plate water heater. The temp of hot water coming out of solar water heater is about 84 0C. We can reasonably assume that the heating in generator is produced at about 80 0C, considering losses of heat.

f. Calculations of solar water heater.

Useful energy (energy absorbed by the collector plate) is given by
Qu= K × S × A
Where,
K=efficiency of collector plate (assume k=0.85)
S=average solar heat falling on earth’s surface=6 kw-hr/m2/day= 250 W/m2
A=Area of collector plates
Now
Heat req. in the generator, Qg = 304.2 KJ/min
= 304.2 × 1000 / 60 J/s
= 5070 W
Hence approximate area of the collector plates required for providing this much amount of energy = 5070 / (250 × K)
= 5070 / (250 × .85)
= 24 square meters (approx)
Total Area of collector plates

$$\boxed{A = 24 \text{ sq m}}$$

Therefore, we can use 4 collector plates of having dimensions of 3 X 2 sq m.
Thus, Qu=0.85 × 250 × 24 = 5070 W= 5070 J/s
The energy absorbed by the collector helps in heating of the water flowing in the tubes of the collector plates.
U = m × Cp × (To-Ti)

Let rate of water flowing through the tubes ,
m = 1.2 kg/min = 0.02 kg/s, (typical example)
Specific heat of water, Cp=4200 J/kg/k
To=Outlet temp. of water in the collector plate
Ti=Inlet temp. of water in collector plate=25 0C
Therefore, Qu = 0.02 × 4200 × (To-25)
i.e. 0.02 × 4200 × (To - 25) = 5070
It gives, To = 84 0C

The temperature (To) should be the inlet temp. of generator, but assuming water loses heat while flowing through the tubes. Also there is certain effectiveness of the generator as a heat exchanger, less that 100 %. Hence net heating in the generator can be assumed to be taking place at 80 0C

Temperature at generator=80 0C

This is the net heat input to the system, which is running as a refrigeration unit of 1 TR capacity.
The work done by the pump for raising the pressure is negligible and hence neglected.

g. COP of the system

The cop of the refrigerating unit can be calculated by using the equation:

$$COP = \frac{Refrigeration\ effect}{Heat\ input\ in\ generator}$$

$$i.e.\ COP = \frac{Q_e}{Q_g}$$

Neglecting pump work

Therefore, COP = 210 / 304.2
= 0.69

Now the COP of the system as a whole (system including solar water heater) can be calculated as

$$COP = \frac{Net\ Refrigeration\ effect\ produced}{Heat\ input\ at\ the\ solar\ collector}$$

Heat input at the collector = Solar constant X area
= 250 W/m2 × 24 m2
= 6000 W = 360 KJ/min

$$COP = \frac{210\ KJ/min}{360\ KJ/min} = 0.58$$

Hence theoretical COP of the whole system comes out to be 0.58

IV. RESULTS AND CONCLUSIONS

As calculated earlier, the heat input required to run the 1 TR vapour refrigeration system, for the operating conditions designed, is about 304.2 KJ/min. This heat in the generator is supplied by the hot water coming from the solar flat plate water heater. For this system the coefficient of performance is also calculated. The results can be summarized as:

- Mass flow rate of cold water=3 Kg/min
  Designed operating conditions:
- Condenser pressure: 10 bar
- Evaporator pressure: 1 bar
- Heat input required (at generator) = 304.2 KJ/min
- Area of the solar collectors required = 24 square meter i.e. 4 plates of 3×2 m 2can be used.
- Output temp of water from solar heater = 84 0C
- COP of refrigerating unit = 0.69
- COP of the whole system = 0.58

In light of the above results, the feasibility of the solar powered vapour refrigeration system has been reasonably proved. The COP values as calculated by us are on a little higher side than the actual COP's, but , because we have assumed ideal processes in heat exchanges etc, this obliquity can be understood.

Hence, a solar water heating unit can be usefully employed for water cooling purposes. In the month of summers, when the solar heating unit is closed and even the solar potential is quite high, the unit can be used for refrigeration. This will actually justify the huge investments made on these units, and the energy source will not remain idle during its peak producing times.

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