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Design of solar powered vapour absorption refrigeration system

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Abstract
The objective of this paper is to design and study an environment friendly solar-powered refrigeration system using a solar flat-plate collector and NH_3-H_2O mixture as the working fluid. The cooling capacity and the coefficient of performance (COP) of the system are analysed (Mathematical modelling) by varying all independent parameters such as condenser pressure, evaporator pressure, mass flow rate, NH_3 concentration and inlet generator temperature. The cooling performance of the system is compared with conventional vapour-compression systems (VCRS) for ammonia refrigerant (R-717).

Keywords: solar powered, generator, condenser, absorber

Introduction

The energy needed to process and circulate air in buildings and rooms to control humidity, temperature, and cleanliness has increased significantly during the last decade especially in developing countries like in India. Energy is a critical need of these countries but they do not have widely distributed readily available supplies of conventional energy resources. Most of the developing countries are characterised by arid climates, dispersed and inaccessible populations and a lack of investment capital and are thus faced with practically insuperable obstacles to the provision of energy by conventional means. In contrast to this solar energy is readily available and is already distributed to the potential users. Because of the diffuse nature of solar energy the developments all over the world have been in smaller units which fit well into the pattern of rural economics.

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.

One of the most common solar air conditioning alternatives is a solar powered absorption system. The solar absorption system is similar in certain aspect to the conventional vapour compression air conditioning system in that the electrical compressor; is replaced with a solar-powered generator and absorber. The most standard pairs of chemical fluids used include lithium bromide-water solution (LiBr-H2O), where water vapour is the refrigerant and lithium bromide is the absorbent, and ammonia-water solution (NH3- H2O) with ammonia as the refrigerant and water the absorbent.

Theory Involved

Vapour Absorption Refrigeration (VARS) System

The vapour absorption refrigeration is heat operated system. It is quite similar to the vapour compression system. In both the systems, there are evaporator and condenser. The process of evaporation and condensation of the refrigerant takes place at two different pressure levels to achieve refrigeration in both the cases. The method employed to create the two pressure levels in the system for evaporation and condensation of the refrigeration makes the two processes different. Circulation of refrigerant in both the cases is also different. In the absorption system the compressor of the vapour compression system is replaced by the combination of “absorber” and “generator”.

Function of components of VARS system

Generator

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

Condenser

The purpose of condenser is to condense the refrigerant vapours. Inside the condenser, cooling water flows through tubes and the hot refrigerant vapour fills the surrounding space. As heat transfers from the refrigerant vapour to the water, refrigerant condenses on the tube surfaces. The condensed liquid refrigerant collects in the bottom of the condenser before traveling to the expansion device. The cooling water system is typically connected to a cooling tower. Generally, the generator and condenser are contained inside of the same shell.

Expansion Device

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

Evaporator

The purpose of evaporator is to cool the circulating water. The evaporator contains a bundle of tubes that carry the system water to be cooled/chilled. High pressure liquid condensate (refrigerant) is throttled down to the evaporator pressure (typically around 6.5 mm Hg absolute). At this low pressure, the refrigerant absorbs heat from the circulating water and evaporates. The refrigerant vapours thus formed tend to increase the pressure in the vessel. This will in turn increase the boiling temperature and the desired cooling effect will not be obtained. So, it is necessary to remove the refrigerant vapours from the vessel into the lower pressure absorber. Physically, the evaporator and absorber are contained inside the same shell, allowing refrigerant vapours generated in the evaporator to migrate continuously to the absorber.

Absorber

Inside the absorber, the refrigerant vapour is absorbed by the lithium bromide solution. As the refrigerant vapour is absorbed, it condenses from a vapour to a liquid, releasing the heat it acquired in the evaporator. The absorption process creates a lower pressure within the absorber. This lower pressure, along with the absorbent‟s affinity for water, induces a continuous flow of refrigerant vapour from the evaporator. In addition, the absorption process condenses the refrigerant vapours and releases the heat removed from the evaporator by the refrigerant. The heat released from the condensation of refrigerant vapours and their absorption in the solution is removed to the cooling water that is circulated through the absorber tube bundle. As the concentrated solution absorbs more and more refrigerant; its absorption ability decreases. The weak absorbent solution is then pumped to the generator where heat is used to drive off the refrigerant. The hot refrigerant vapours created in the generator migrate to the condenser. The cooling tower water circulating through the condenser turns the refrigerant vapours to a liquid state and picks up the heat of condensation, which it rejects to the cooling tower. The liquid refrigerant returns to the evaporator and completes the cycle.

Flat-plate collectors

The construction of a flat-plate collector is shown in Figure below. The basic parts noted are a full-aperture absorber, transparent or translucent cover sheets, and an insulated box. The absorber is usually a sheet of high-thermal-conductivity metal with tubes or ducts either integral or attached. Its surface is painted or coated to maximize radiant energy absorption and in some cases to minimize radiant emission. The cover sheets, called *glazing,* let sunlight pass through to the absorber but insulate the space above the absorber to prohibit cool air from flowing into this space. The insulated box provides structure and sealing and reduces heat loss from the back or sides of the collector.

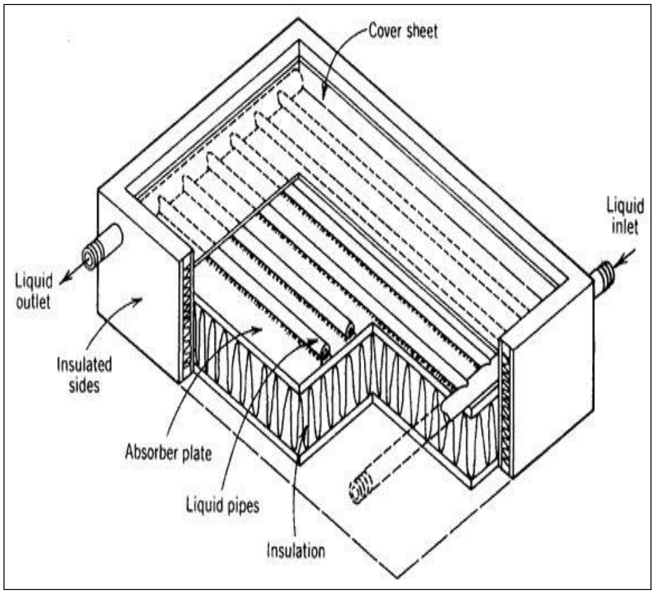

Fig 1

R717 Gas Properties

Table 1

Molecular Weight	**Molecular weight : 17.03 g/mol**
	Melting point : -78 °C
Solid phase	Latent heat of fusion (1,013 bar, at triple point) : 331.37 kJ/kg
	Liquid density (1.013 bar at boiling point) : 682 kg/m^3
	Liquid/gas equivalent (1.013 bar and 15 °C (59 °F)) : 947
	vol/vol
Liquid phase	Boiling point (1.013 bar) : -33.5 °C
	Latent heat of vaporization (1.013 bar at boiling point) : 1371.2
	kJ/kg
	Vapor pressure (at 21 °C or 70 °F) : 8.88 bar

	Critical temperature : 132.4 °C
Critical point	Critical pressure : 112.8 bar
	Gas density (1.013 bar at boiling point) : 0.86 kg/m3
	Gas density (1.013 bar and 15 °C (59 °F)) : 0.73 kg/m3
	Compressibility Factor (Z) (1.013 bar and 15 °C (59 °F)) :
Gaseous phase	0.9929
	Specific gravity (air = 1) (1.013 bar and 21 °C (70 °F)) : 0.597
	Specific volume (1.013 bar and 21 °C (70 °F)) : 1.411 m3/kg
	Heat capacity at constant pressure (Cp) (1.013 bar and 15 °C
	(59 °F)) : 0.037 kJ/(mol.K)
	Heat capacity at constant volume (Cv) (1.013 bar and 15 °C
	(59 °F)) : 0.028 kJ/(mol.K)
	Ratio of specific heats (Gamma:Cp/Cv) (1.013 bar and 15 °C
	(59 °F)) : 1.309623
	Viscosity (1.013 bar and 0 °C (32 °F)) : 0.000098 Poise
	Thermal conductivity (1.013 bar and 0 °C (32 °F)) : 22.19
	mW/(m.K)
	Solubility in water (1.013 bar and 0 °C (32 °F)) : 862 vol/vol
Miscellaneous	Autoignition temperature : 630 °C

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 (P_e) are determined the corresponding various other points and condition lines for components like absorber, generator, heat exchangers etc. can be subsequently fixed.

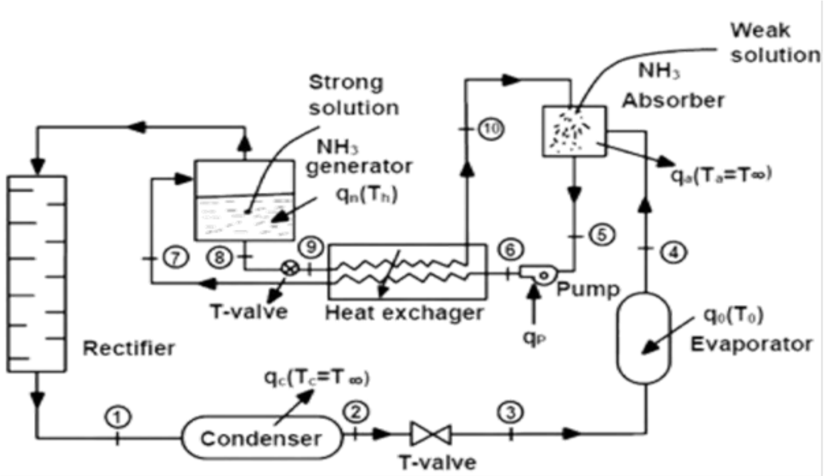

Fig 2

A. Condenser Pressure (P_c)

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 room temperature of 25 ^{0}C. I.e. condensing temperature is T_c= 25 ^{0}C. For condensing ammonia vapours at 25^{0}C, 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.

Therefore, T_c = 25 ^{0}C.

Corresponding pressure Pc=10 bar *(from refrigeration table of ammonia R-717)*

B. Evaporator Pressure (P_e)

The evaporator pressure can be fixed according to the minimum temperature required to be maintained in the evaporator chamber. 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 ^{0}C.

Therefore Atmospheric pressure i.e. P_e = 1 atm. The corresponding saturation temperature in the evaporator (ammonia vapours) becomes -33 ^{0}C *(From refrigeration table of ammonia R-717).*

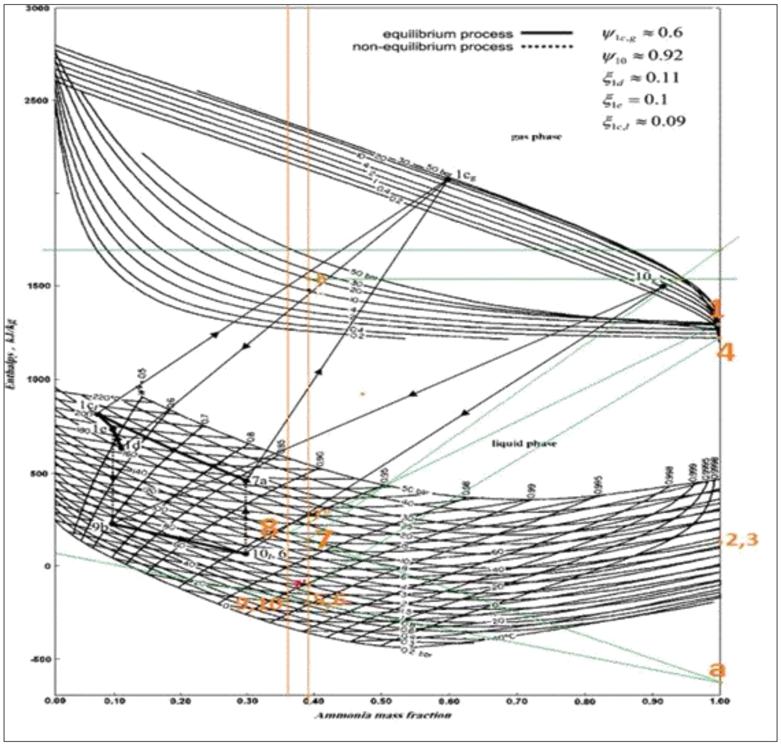

Fig 3

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 NH_3 saturated vapour at condenser pressure Pc=10 bar and concentration C=1. Point 2 represents pure NH_3 saturated liquid at Pc=10 bar and C=1. This point is marked in liquid region. Point 3 represents the condition of pure NH_3 (wet) but at pressure P_e = 1 bar and C = 1. Point 2 coincides with point 3 as 2-3 is a throttling process in which enthalpy remains constant. The point 4 represents condition of pure NH3 at pressure P_e these are saturated vapours which absorbs heat in evaporator and converts from wet vapour to saturated vapour. This point is marked in vapour region. So Enthalpy @ point 1, 2, 3 as shown in the diagram is h1= 1626.6 KJ/Kg h2= h3= 460 KJ/Kg h4= 1561.9 KJ/Kg (from refrigeration table of ammonia R-717).

C. Refrigerating effect

We take 0.1 ton of refrigeration system for our system. This value is approximate value we got from {http://easycalculation.com/weather/embedded_ac-tonnage.php}

The refrigerating effect produced or the heat absorbed by ammonia refrigerant in the evaporator is

Q_e= h4 – h3 KJ/Kg of ammonia.

M_r × (h4 – h3) = 0.1 TR (1 TR= 210 KJ/min)

M_r × (h4 – h3) = 21 KJ/min

M_r× (1561.9 - 460) = 21

M_r= 0.01906 Kg/min.

Now, the temp of the water going inside the generator is more than 90 ^{0}C (about 94 ^{0}C). That is, taking the temperature in the generator T_g = 90 ^{0}C (assuming losses). Thus the point 8 can be marked on the pressure enthalpy chart where the constant temp line of 90 ^{0}C intersects the pressure line of 10 bar. Point 8 represents the hot weak liquid having concentration C_w inside the generator. Thus the corresponding concentration of the weak solution can be directly noted down from the chart as C_w = 0.37. 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 C_5, 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 0.01906 Kg/min is required to be flown across the evaporator for steady state.

Thus the degasifying factor becomes 1.So the concentration of strong aqua solution becomes

C_5= C_w + 0.01906
=0.38906
=0.39

Thus taking the concentration of strong solution to be
Cs =C_5 = 0.39

Hence now we know the concentration and pressure at point 5, thus point 5 can be located on the chart at C_5= 0.39 and pressure Pc = 10 bar

Point 6: This is the condition of the aqua solution whose concentration C_5 = 0.39, but the pressure is increased from P_e to P_c 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 C_7 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 P_e as it passes through the pressure reducing valve.

D. 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 P_e 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.

E. Generator

In generator, strong aqua is heated by supplying heat Q_g. The strong aqua enters into the generator at condition 7 and pure NH_3vapour 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.

F. Calculation

A. Mass flow rate of ammonia as refrigerant

M_r= 0.01906 kg/min

B. Heat removed in the evaporator [Refrigerant Effect]

$Q_e = M_r (h_4 – h_3)$ = 0.1 TR = 21KJ/min

If M_w is rate of cold water flowing in evaporator. Then,

$M_w * C_p * \Delta T = 21$

If $\Delta T=16^0C$ then,

$M_w= (21)/ (16 * 4.18)$

M_w= 0.313 Kg/min

C. Heat removed in condenser by the circulated cooling water is given by the equation

$Q_c= M_w * (h_2-h_1)$

0.01906 (1626.6 – 460)

22.23 KJ/min

Thus, Q_a = 266.4 KJ/min

D. Heat removed from absorber

When the NH_3 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

$Q_a= M_r (h_{7''} – h_5)$

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

$= M_r (h_4 – h_a)$

=0.01906* (1561.9 – 65)

=28.53 KJ/min.

Now the resultant aqua is at condition 7”, which loses heat up to condition 5.

Temp at 7” => $T_{7''}$ = 100 ^{0}C [from c-h chart]

Say, water gets heated to a temp of 100 ^{0}C from 25 ^{0}C while removing heat from absorber

If M_w = mass of cooling water required in absorber

$M_w * C_p * \Delta T = 28.53$

$M_w = [28.53]/ [4.18*(100-25)]$

M_w = 0.091 kg/min.

That is, the mass of cooling water required in absorber is 0.0191 Kg/min.

E. Heat given in the generator

Q_g= heat supplied to generator

Q_d = heat removed from water vapour

Net heat removed per kg of aqua

$Q_g – Q_d = M_{NH3} (h_{7''} – h_7)$

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 NH_3 is given by

$Q_g – Q_d = M_{NH3} (h_1 – h_a)$

$Q_g = Q_d + M_{NH3} (h_1 – h_a)$

$= Q_d + (0.01906) [1626.6 - 65] = Q_{d +} 29.764$

Now for finding out Q_d separately, extend the vertical line 7-7‟ till it cuts the auxiliary line P_c and mark point „b‟ as shown. Then draw a horizontal line through b which cuts P_c 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 Q_d is given by

$Q_d = M_{NH3} (h_{12} – h_1)$

= (0.01906) [1699 – 1626.6] = 1.2932

Now using equation $Q_g – Q_d$ = (h1 - ha) we have

Q_g = 1.2932 + 29.764 = 31.143 KJ/min

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

Q_g = 31.143 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 94 ^{0}C. We can reasonably assume that the heating in generator is produced at about 90 ^{0}C, considering losses of heat.

F. Calculation of solar water heater

Useful Energy absorbed by collector plate is given by Q_u = K * S * A
Where K = efficiency of the collector plate
S = average solar heat falling on earth‟s surface
A = area of collector plate

Heat required in the generator
$Q_{g\,=}$ 31.143 KJ/min = 519 W

Hence approximate area of the collector plates required for providing this much amount of energy = 519 / (S× K)
Let‟s assume K= 0.85 [for Copper flats plate collector] S = 14.4 KW-hr/m^2/day = 600 W/m^2
[http://zebu.uoregon.edu/disted/ph162/l4.html]
Hence approximate area of the collector plates required for providing this much amount of energy in generator
Area of collector plate A = 519/ (600*0.85) = 1.017 m^2
If we use Q_u= 519 W then we get small value of mass flow rate. To increase mass flow rate we increase area of flat plate collector to 1.5 m^2.
Then corresponding Q_u= KSA = (0.85) (600) (1.5) = 765 W.
This energy is absorbed by the collector plate which helps in heating of the water flowing in the tubes of collector plate
Rate of water flowing through the tubes is M
= M* C_p * ΔT = M* C_p *(T_0 - T_i) Where U = Q_u= 765 W
C_p of water = 4180 KJ/Kg*K
T_i = inlet temp of water in collector plate = 25 ^{0}C
Assume rate of water flowing through the tubes
M = 0.159 Kg/min =. 00265 Kg/sec.
U = M* C_p * ΔT = M* C_p *(T_0 - T_i)
765 =. 00265*4180*(T_0 - 25) T_0= 94 ^{0}C

The temperature (T_o) should be the inlet temperature 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 90 ^{0}C.
After loss from Heat Exchanger we take T_0 = 90 ^{0}C.
This is the net heat input to the system, which is running as a refrigeration unit of 0.1 TR capacity. The work done by the pump for raising the pressure is negligible and hence neglected.

COP of the system

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

$$\mathrm{COP} = \frac{\text{Refrigeration Effect}}{\text{Heat Input in Generator}}$$

$$\mathrm{COP} = \frac{\mathrm{Qa}}{\mathrm{Qg}}$$

$$\mathrm{COP} = \frac{21}{31.143}$$

$$\mathrm{COP} = 0.674$$

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

$$\mathrm{COP} = \frac{\text{Net Refrigeration Effect Produced}}{\text{Heat Input at Solar Collector}}$$

Heat input at solar collector = 600 * 1.5
= 900 J/sec
= 54 KJ/ min.
COP = 0.388

Hence theoretical COP of the whole system comes out to be 0.388.

Material Selection

As R717 is highly corrosive selection of the material to be used in the design is a great concern. Material should not only be non-corrosive with R717 but also withstand the pressure developed in the system. Following are some material that can be used for making system and their compatibility with R717.

Table 2

Material (Metals)	Compatibility
Aluminium	Satisfactory
Brass	Non recommended
Copper	Non recommended
Ferritic Steels (e.g. Carbon steels)	Satisfactory
Stainless Steel	Satisfactory

As ammonia is widely used above all in industrial refrigeration systems, steel has predominantly been used for the essential construction elements, such as pipes, heat exchangers and containers in ammonia cycles. In order to gain ground for ammonia applications in the sector of commercial refrigeration, technologies are in demand, which refrigeration technicians are familiar with from HFC and CFC refrigeration systems (soldering and separable fasteners). In this respect aluminum offers the best prerequisites as a construction material.

Properties of aluminum (Al)

In comparison to those of copper (Cu) predominantly used in HFC cycles

Table 3

		Al	**Cu**
Density	10^3 kg/m³	2.7	8.9
Thermal conductivity	W/m K	230	310
Electrical conductivity ca.	m/W mm²	36	58
0.2 yield strength ca.	N/mm²	60	160
Thermal expansion	106 1/K	23.8	16.2
Melting Point	°C	660	1083

Advantageous properties of aluminum are

- Cost efficient cold plasticity
- Good Machinability
- Toughness at sub-zero and, therefore, suitable for the evaporation temperature range of below –10°C
- Solderability and Weldability
- Hygienic safeness
- Reusability

Aluminium Alloys

Aluminium is not just aluminium, In fusible condition it can be alloyed to Copper, Magnesium, Manganese, Silicon, Iron, Titanium, Beryllium, lithium, Chromium, Zinc, Zirconium and Molybdenum in order to foster certain characteristics or prevent other unrequested characteristics.

Regulations for the use of aluminium

According to the draft of EN 378, Aluminium and Aluminium alloys can be used in any component of the refrigeration cycle if their solidity is sufficient high and they are compatible with ammonia.

Stress corrosion cracking behaviour

The aluminium alloys intended for the use in ammonia cycles are not affected by stress corrosion cracking.

Connecting Technology

The inseparable connections of pipes by hard-soldering of the couples aluminium/aluminium and aluminium/austenitic Cr Ni steels are mechanically solid and corrosion-resistant. In the case of soldered joints of aluminium with ordinary steels or low-alloy steels, corrosion has to be expected at the junction. By rolling aluminium pipes into steel panels, shell-and-tube heat exchangers can be manufactured permanently tight.

Conclusion

Aluminium alloys have proved reliable as construction materials in ammonia cycles. Construction elements of aluminium alloys offer safe solutions with regard to corrosion resistance and mechanical resistance. Therefore, the advantages of the refrigerant ammonia with regard to considerably smaller dimensioning of pipes, fittings and valves can be combined with the advantages of the construction material aluminium.

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