Design Analysis Of 3 TR Aqua Ammoniavapour Absorption Refrigeration System

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Abstract: This paper presents the design of vapour absorption refrigerating system of capacity 3 tonne based on the basic concepts of thermodynamic principles. In design the area of all the major components of the system is calculated on the basis of enthalpy parameters at different points in the system. The data is analysed using the first and second laws of thermodynamics to determine the refrigerating effect, the net heat required to run the system and the coefficient of performance (COP). The COP of the system is calculated as 0.2079 working between the condenser pressure of 10.7 bar and evaporator pressure of 4.7 bar. Ammonia is used as the refrigerant in the system and water as absorbent in the physico-chemical process.

Keywords: Ammonia, Refrigerant, Heat Exchangers, Absorption System, Absorbent, Thermodynamics

1. Introduction

Refrigeration is the process of removing heat from an enclosed space, or from a substance, and moving it to a place where it is unobjectionable. The primary purpose of refrigeration is lowering the temperature of the enclosed space or substance and then maintaining that lower temperature. The term cooling refers generally to any natural or artificial process by which heat is dissipated. Cold is the absence of heat, hence in order to decrease a temperature, one "removes heat", rather than "adding cold." In order to satisfy the Second Law of Thermodynamics, some form of work must be performed to accomplish this. This work is traditionally done by mechanical work but can also be done by magnetism, laser or any source of heat (exhaust waste heat, steam etc.) The equipment employed to maintain the system at low temperature is termed as refrigeration system and the system which is kept at low temperature is called refrigerated system. Refrigeration is generally produced by one of the following three ways:-

a) By Melting of a Solid
b) By Sublimation of a Solid
c) By Evaporation of a Liquid

The commonly used method of refrigeration is by mechanical vapour compression refrigeration (VCR) system as it is an efficient method as the energy input is the shaft work.

The work required is relatively large because of compression of the vapours which undergoes large changes in specific volume. For an ideal vapour compression having coefficient of performance of 4, the shaft work will be 25% of the cooling effect obtained. The object of a compressor in the vapour compression refrigeration system is to withdraw the vapours from the evaporator and compress them to such pressure corresponding to which the saturation temperature is higher than the cooling agent in the condenser, so that the high pressure vapours can reject heat in the condenser and be ready to expand to the evaporator pressure again. The vapour compression refrigeration system requires high grade energy in the form of shaft work to drive the compressor, with the concomitant disadvantage of high vibrations and noise of the rotating machines, whether it is a reciprocating, rotary or centrifugal type.

A Vapour Absorption Refrigeration (VAR) System is similar to a Vapour Compression Refrigeration (VCR) System. In both systems the required refrigeration is provided by refrigerants vaporizing in the evaporator. However, in the VAR System, a physico-chemical process replaces the mechanical process of the VCR system and heat rather than a mechanical and electrical energy is used. In the absorption refrigeration system the vapour is drawn from the evaporator by absorption into liquid having high affinity for the refrigerant. The refrigerant is expelled from the solution by application of the heat and its temperature is also increased. This refrigerant in the vapour form passes to the condenser where heat is rejected and refrigerant gets liquefied. This liquid again flows to the evaporator at the reduced pressure and cycle is completed. The elimination of the necessary shaft work has been the prime reason for the economic success of vapour absorption system. As these systems require only low grade energy in the form of heat and due to limited energy sources and growing demand, there is a concern in the scientific community to develop energy efficient systems.

Refrigeration and Air conditioning systems consume considerable amount of energy around the world. In order to reduce this share some alterations need to be searched for example for cooling application, Vapour absorption system which is basically driven by low grade energy such as waste heat, solar energy is coming in picture for the last few decades. The advantages of this system lie in the possibility of utilizing of waste energy from industrial plants as well as of using solar energy. Aqua ammonia system is employed for applications below 32℉ (0℃) in which the refrigerating fluid is ammonia and absorbent or carrier is water. The combination of aqua ammonia has been particularly attractive because of the following advantages:

a) Its performance is better than that of Fluoro Carbon refrigerant.

b) It is free from the limitation imposed by the high freezing temperature of the refrigerant and low crystallization temperature of the solution, as in lithium bromide water system, or extreme corrosiveness in ammonia sodium Thio-Cyanate system so the controls in Ammonia water machines are simpler.

The only disadvantage with ammonia water system is the volatile nature of the water used as the absorbent. However this difficulty can be overcome by incorporating a properly designed rectification column. While operating under ideal conditions the overall COP of the Ammonia water cycle is 0.2-0.5.

2. Working Principle of Ammonia Absorption systems

The technology of absorption refrigeration plants has been used for cooling purposes for over a hundred years now. In plants of today, the most modern technology is being used for the design of the components and the control strategy, which, of course, improves the economic value and the reliability of the plants considerably. In a cooling machine, the refrigerant evaporates at low temperature and low pressure. The vapour is extracted from the evaporator, than transformed to a higher pressure and liquefied in the condenser.

The main difference between a compression and an absorption cycle is that the former needs mechanical energy as a driving source for the compressor and the latter needs thermal energy for the desorber and only a small amount (2% of the driving energy) of electricity for the liquid pump.

In some cases, it is useful to build Absorption Refrigeration Plant's (ARP) with several stages, for instance when the temperature of the driving energy is not high enough.

Ammonia vapour is vigorously absorbed in water. So when low pressure ammonia vapour from the evaporator comes in contact in the absorber with the weak solution (the concentration of ammonia in water is low), coming from the generator, it is readily absorbed, releasing the latent heat of condensation. The water has the ability to absorb very large quantities of ammonia vapour and the solution thus formed, is known as aqua-ammonia.

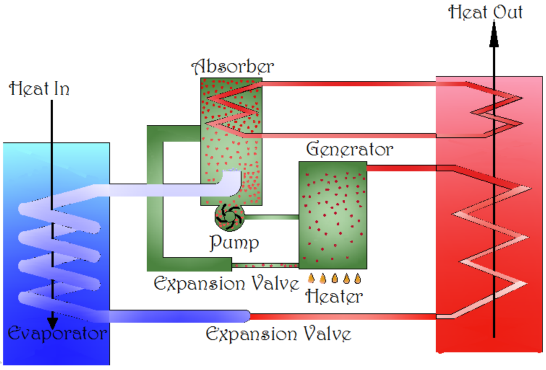

Figure 1. Basic vapour absorption refrigeration system

The absorption of ammonia vapour in water lowers the pressure in the absorber which in turn draws more ammonia vapour from the evaporator and thus raises the temperature of solution. The absorber is cooled by the circulating water thus absorbing the heat of the solution (Q_A), and maintaining a constant temperature. The strong solution (rich in ammonia) thus formed in the absorber is pumped to the generator by the liquid pump. The pump increases the pressure of the strong solution. The strong solution of Ammonia is heated in the generator, where heat (Q_G) is supplied from an external source such as steam, electricity, Kerosene lamp, waste heat and solar radiation etc. Since the boiling point of ammonia (-33.3℃) is less than that of water (100 ℃), the ammonia vapour is given off from the solution at high pressure, and the weak solution returns to the absorber through a pressure reducing valve. The Ammonia vapour leaving the generator condenses in the condenser releasing the heat of condensation (Q_C) to the surroundings or cooling water and is throttled by the expansion valve and then evaporates by absorbing the heat of evaporation (Q_E) from the surrounding or the brine to be chilled.

3. Working Fluid for the Absorption Refrigeration Systems

Performance of absorption refrigeration systems is critically dependent on the chemical and thermodynamic properties of the working fluid. A fundamental requirement of absorbent/refrigerant combination is that, in liquid phase, they must have a margin of miscibility within the operating temperature range of the cycle. The mixture should also be chemically stable, non-toxic, and non-explosive. In addition to these requirements, the following are desirable:

a The elevation of boiling point (the difference in boiling point between the pure refrigerant and the mixture at the same pressure) should be as large as possible.

b Refrigerant should have high heat of vaporization and high concentration within the absorbent in order to maintain low circulation rate between the generator and the absorber per unit of the cooling capacity.

c Transport properties that influence heat and mass transfer, e.g., viscosity, thermal conductivity, and diffusion coefficient should be favorable.

d Both refrigerant and absorbent should be non-corrosive, environmental friendly, and economical.

There are some 40 refrigerant compounds and 200 absorbent compounds available. However, the most common working fluids are water/ammonia and LiBr/water. Since the invention of absorption refrigeration systems, water/ammonia has been widely used for both cooling and heating purposes. The main properties are:

a Ammonia (refrigerant) and water (absorbent) are highly stable for a wide range of operating temperature and pressure.

b Ammonia has a high latent heat of vaporization, which is necessary for efficient performance of the system. Its latent heat of vaporization at -15℃ is 1315kJ/Kg. Thus, large refrigerating effects are possible with relatively small size machinery.

c Its boiling point at atmospheric pressure is -33.3 ℃ & freezing point is -77 ℃ The low boiling point makes its possible to have refrigeration at temperatures considerably below 0 ℃ without using pressure below atmospheric in the evaporator.

d It has highest refrigerating effect per Kg of refrigerant

e The leakage of this refrigerant may be quickly & easily detected by the use of burning sulphur candle which in the presence of ammonia will form white fumes of ammonium sulphite.

f Ammonia is toxic in nature. This refrigerant attacks copper & bronze in the presence of a little moisture but does not corrode iron and steel.

g It has high efficiency.

h It has low cost.

i Low weight of liquid circulated per tonne of refrigeration

j Since both ammonia and water are volatile, the system require a rectifier to strip away water that normally evaporates with ammonia.

k It is environmental friendly.

4. Design Conditions for the 3TR Aqua Ammonia Refrigeration System.

The literature values for the design of the Aqua Ammonia vapour absorption system are:

Capacity of system = 3TR(10.548KW)
Concentration of NH_3 in refrigerant, X_r = 0.98
Concentration of NH_3 in Solution, X_s = 0.42
Concentration of NH_3 in absorbent, X_w = 0.38
Temperature of the evaporator, T_E = 2℃
Generator or condenser pressure, P_H = 10.7 bar
Evaporator pressure, P_L = 4.7 bar
Temperature of the Condenser, T_C = 54℃
Temperature of the Absorber, T_A = 52℃
Temperature of the Generator, T_G = 120℃

Table 1. Values of mixture at various state points

State Points	Temperature in ℃	Pressure in bars	SpecificEnthalpy h in KJ/Kg
1	54	10.7	1135
2	54	10.7	200
3	2	4.7	200
4	2	4.7	1220
5	52	4.7	0
6	52	10.7	0
7	120	10.7	255
8	120	4.7	255

Using the enthalpy-concentration diagram for aqua ammonia, at various concentrations of ammonia/water and corresponding saturation pressure, the corresponding enthalpy (KJ/Kg) and temperature (OC) can be calculated and on the basis of this enthalpy and various mass flow rates calculated, the heat transfer in the various components of the vapours absorption system are calculated. On the basis of this heat transfer the various components are designed. The enthalpy-concentration diagram has liquid saturation region. If the liquid is saturated at a given pressure and temperature. The enthalpy can be calculated by plotting a point corresponding to the given concentration. The other region are saturated vapour and superheated vapour region.

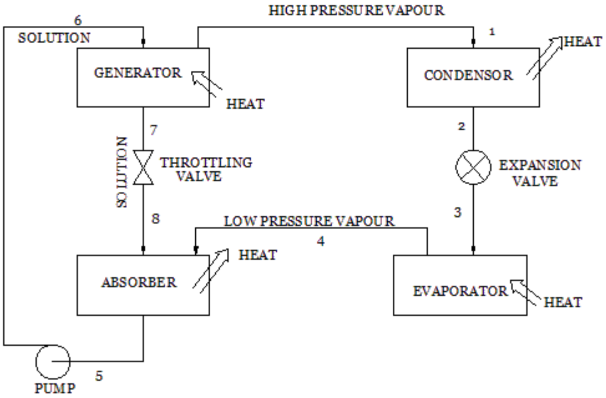

Figure 2. Schematic diagram of vapour absorption refrigeration system

5. Calculation Equations

Mass Flow Rate

Consider State Point 2:- (saturated liquid)

$$P_2=10.7br$$

$$X_2=0.98$$

Using the enthalpy concentration diagram for Ammonia / Water

We get:

$$T_2 = 54℃$$

$$h_2 = 200\ KJ/Kg$$

State Point 3: (expansion of refrigerant through expansion valve from high pressure to low pressure at constant enthalpy)

$$h_2 = h_3 = 200\ KJ/Kg$$

$$T_3 = 2℃$$

$$P3 = 4.7\ bar$$

State Point 4: (extraction of heat by low pressure ammonia vapour in the evaporator)

Saturation Pressure in evaporator;

$$P4 = 4.7\ bar$$

Evaporator temp;

$$T_4 = 2℃$$

Using Enthalpy concentration diagram; considering the ammonia vapour as saturated.

$$h_4 = 1220\ KJ/Kg$$

Heat Extracted by evaporator;

$$Q_E = m_r \times (h_4\text{-}h_3)$$

m_r = Mass flow rate of refrigerant

Given that

$$Q_E = 3.516\ KW$$

$$\therefore 10.548 = m_r \times (1220\text{-}200)$$

$$m_r = 10.341 \times 10^{-3}\ Kg/s$$

$$\therefore\ m_r = 10.341\ gm/sec$$

Using Mass Balance Equation:

Mass Of solution (m_s)=Mass of refrigerant(m_r)+ Mass of absorbent(m_w)

$$m_s = m_w + m_r$$

Using Material Balance Equation For NH_3;

$$m_s X_s = m_r X_r + m_w X_w$$

$$(m_w + m_r)\ X_s = m_r X_r + m_w X_w$$

$$(m_w + 10.341) \times 0.42 = 10.341 \times 0.98 + m_w (0.38)$$

$$\therefore\ m_w = 144.774\ gm/sec$$

$$\therefore\ m_s = m_w + m_r$$

$$= 144.774 + 10.341$$

$$m_s = 155.115\ gm/sec$$

Design of Evaporator

Evaporator is an equipment in which refrigerant vapourizes to generate the desired refrigeration. It is also known as chiller. Considering the evaporator made of tubes and air cooled.

Let air inlet temperature to evaporator

$$t_{h1} = 30℃.$$

Air outlet temp;

$$t_{h2} = 5℃.$$

$$\Delta\theta_1 = 30\text{- } 2 = 28℃$$

$$\Delta\theta_2 = 5\text{-}2 = 3℃$$

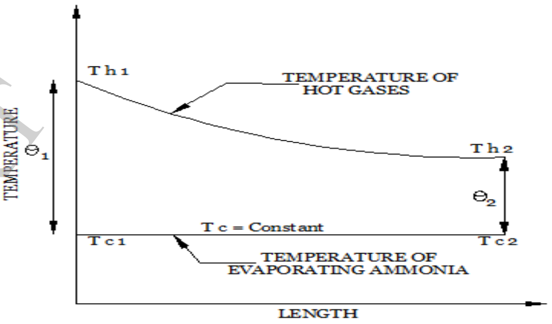

Figure 3. Temperature changes in evaporator

$$\therefore\ [LMTD\ ] = \theta_m = \frac{\Delta\theta_1 - \Delta\theta_2}{\ln(\Delta\theta_1 / \theta_2)}$$

LMTD (θ_m) = (28-3) / ln(28/3) = 11.193℃

Assuming, Overall heat transfer coefficient (U)=1000 W/m^2

Assuming, correction factor (F) = 1

$$\therefore\ Q_E = FUA\ \theta_m$$

$$10.548 \times 1000 = 1 \times 1000 \times A_E \times 11.193$$

Area of the evaporator $A_E = 0.9423\ m^2$

Considering the number of evaporator tubes (n) = 30

Length of each tube (L) = 70cm

Diameter of evaporator tube (D) = to be calculated

$\therefore$ the effective area of evaporator (A_E)=n × π × D × L

$$0.9423 = 30 \times \pi \times D \times 0..7$$

$$\therefore\ D = 1.42cm = 0.55\ inches.$$

Design of Condenser

The function of the condenser is to remove the heat of the hot vapour refrigerant.

State point 1 Ammonia Vapour Entering the condenser shell as a Saturated Vapour

$$P_1 = 10.7 \text{ bar}$$
$$X_r = 0.98$$

Using h-x Diagram for Ammonia/Water

$$T_1 = 54℃$$
$$h_1 = 1135 \text{ KJ/Kg}$$

Heat rejected by condenser

$$Q_C = m_r \times (h_1\text{-}h_2)$$
$$Q_C = 10.341 \times 10^{-3} \times (1135\text{-}200)$$
$$\therefore Q_C = 9.66 \text{ KW}$$

The cooling medium used is air.

Inlet temperature of air is (t_{c1}) = 30℃.

Exit temperature of cooling water (t_{c2}) = 45℃.

$$\Delta\theta_1 = 54\text{- }25 = 29℃$$
$$\Delta\theta_2 = 54 - 45 = 9℃$$

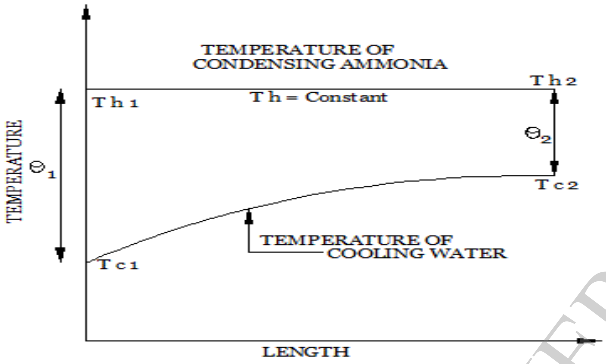

Figure 4. Temperature changes in condenser

$$\therefore \text{LMTD}\theta_m = \frac{\Delta\theta_1 - \Delta\theta_2}{\ln(\Delta\theta_1/\Delta\theta_2)}$$

$$\text{LMTD } (\theta_m) = (29\text{-}9) / \ln(29/9) = 17.09℃$$

Assuming, Overall heat transfer coefficient (U)=1000 W/m^2

Assuming, correction factor (F) = 1

$$\therefore Q_C = \text{FUA } \theta_m$$
$$9.66 \times 1000 = 1 \times 1000 \times A_C \times 17.09$$

Area of the Condenser $A_C = 0.56 \text{ m}^2$

Considering the number of Condenser tubes (n) = 30

Length of each tube (L) = 70 cm

Diameter of Condenser tube (D) = to be calculated

∴ the effective area of Condenser $(A_C) = n \times \pi \times D \times L$

$$0.56 = 30 \times \pi \times D \times 0.70$$
$$\therefore D = 0.85 \text{ cm} = 0.34 \text{ inches.}$$

Design of Generator

State Point 5: strong solution entering the pump as saturated liquid

$$P_5 = 4.7 \text{ bar}$$
$$X_s = 0.42$$

Using enthalpy-concentration diagram;

$$T_5 = 52℃$$
$$h_5 = 0 \text{ KJ/Kg}$$

State Point 6: high pressure saturated strong solution entering the generator

$$P_6 = 10.7 \text{ bar}$$
$$X_s = 0.42$$
$$h_5 = h_6 = 0 \text{ KJ/Kg}$$

State point 7: weak solution leaves the generator at saturation temperature of generator

$$P_7 = 10.7 \text{ bar}$$
$$X_w = 0.38$$

Using h-x diagram

$$h_7 = 255 \text{ KJ/Kg}$$
$$T_7 = 120℃$$

Using energy balance for generator

$$Q_G = \text{Heat added to generator}$$
$$Q_G = m_r h_1 + m_w h_7 - m_s h_6$$
$$= (10.341 \times 1335) + (144.774 \times 255) - (144.774 \times 0)$$
$$= 50.722 \text{ KW}$$

Assuming the heat is supplied to ammonia generator by condensing steam at 2 bar and 90% dry. Assuming the only latent heat of steam is used for this purpose.

From steam table at 2 bar

$$h_{fg} = 2201.6 \text{ KJ/Kg}$$

∴ Mass flow rate of steam to generator=(17.1435 × 60)/2201.6

=0.04672 Kg/min

This heat can be added by using solar energy

$$\therefore Q_g = I_s \times \eta_s \times A_c$$

Where I_S (insolation) = 600 W/m^2

η_S (efficiency of collector) = 30 %

∴ Effective area of collector = $Q_G / I_S \times \eta_S$ = 95.24 m^2

This heat is added by using a heating element of the required wattage.

Design of Absorber

Heat rejected in the absorber

$$Q_A = m_w h_8 + m_r h_4 - m_s h_5$$
$$\therefore Q_A = (144.774 \times 255) + (10.341 \times 1220) - (144.774 \times 0) = 49.5 \text{ KW}$$

Considering the absorber to be direct contact heat exchanger in which the weak solution from the generator mixes with the ammonia gas from the evaporator and due to the direct mixing the heat is rejected. Air is used as cooling medium.

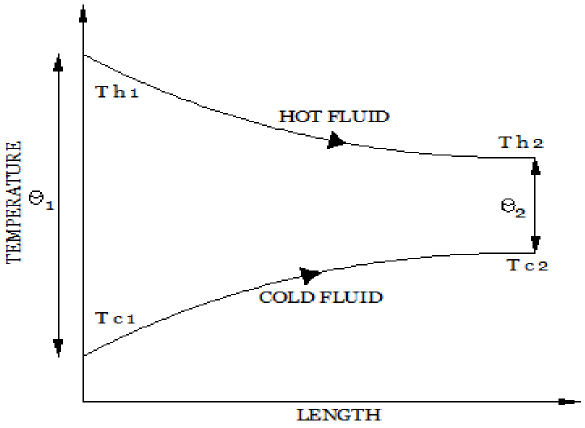

Figure 5. Temperature changes in absorber

COP of System

Now, COP = Q_E/Q_G (Neglecting pump work Wp)

COP = 10.548/50.722

COP = 0.2079

The COP of the system can be enhanced by using:-

a Liquid-Vapour heat exchanger (Sub cooler)
b Liquid-Liquid heat exchanger

6. Conclusions

This paper explains about the basic design of aqua ammonia vapour absorption system and its comparison with vapour growing demand, there is a concern in the scientific community to develop energy efficient refrigeration and air conditioning systems. Vapour absorption systems are designed to use steam, exhaust gases, waste heat etc. Solar power is coming in the picture for the last few decades. The various components of 3TR aqua ammonia vapour absorption system are designed at a given concentration of mixture. The main components of the system designed are Evaporator and Condenser as air cooled single tube heat exchanger. The Absorber and Generator are compression system. Due to the limited energy sources and direct mixing type heat exchangers. The effective area of each component is calculated and on the basis of these calculated values, the various components can be fabricated. All the components can be fabricated using mild steel due to the corrosive nature of ammonia on copper, aluminium, brass etc. The over all estimated cost of the project is approximately Rs. 48,690/ as per the market survey.

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