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A Study to find out the Optimum Refrigeration Cycle for the Proposed Central Air Conditioning System of RUET Auditorium

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Abstract

Air conditioners are commonly operated by vapor compression or vapor absorption systems, depending on the type of energy source available. In this article, the main components of the central air conditioning system of RUET auditorium are designed, with vapor compression and ammonia-water vapor absorption systems respectively. Besides, the coefficients of performance are calculated for these systems. Ammonia is chosen as refrigerant rather than CFCs to ensure environmental safety. After the design work, a cost analysis is made, considering installation and operating costs. The cost analysis shows that the installation cost of the vapor absorption system is nearly 74% higher than the vapor absorption system whereas the operating cost of this system is comparatively 30% lower. Finally, the costs of these systems are expressed in terms of equivalent annual cost and a comparison is made with respect to the coefficient of performance and equivalent annual cost to find out the optimum system.

Keywords: Vapor compression system, Vapor absorption system, CFC, Coefficient of performance.

1. Introduction

Air conditioning systems have become an essential part of modern theaters and auditoriums, especially in a place like Rajshahi, where scorching heat waves strike in the summer. For large scale air conditioning, a central system is more efficient and economical than split or window systems. Moreover, in a place like an auditorium, where it is mandatory to keep the environment as silent as possible, a central air conditioning system is more convenient since all the major components are kept outside.

All over the world, scientists and engineers are trying to replace chlorofluorocarbons (CFC) by a harmless alternative, considering environmental issues. In many places, ammonia has been used as a replacement for CFC with great success [1]. That's why ammonia is chosen as the refrigerant in this paper. The main focus of this paper is to design the main components and make a comparison between two different types of air conditioning systems (vapor compression system and vapor absorption system) to choose the optimum system for RUET auditorium. The cooling load of the auditorium is 154TR. [2].

2. Design of the Main Components of Vapor Compression System

An ideal vapor compression system is consists of a few main components like compressor, condenser, and evaporator. An expansion device is also used through which condensed refrigerant expands. To design these components, the following assumptions are made. Firstly, the designed cycle is a theoretical vapor compression cycle that delivers dry saturated vapor after compression. Secondly, the vapor comes out from the compressor is not superheated, sub-cooled or undercooled. Finally, compressed vapor gets condensed at 48.9℃ and evaporates at 14℃ [3].

Design of Evaporator

Air conditioning systems are designed, considering extreme temperature conditions. In Bangladesh, temperature raises to the maximum point in June and in Rajshahi, the average outdoor temperature is 39℃ in this period. The design temperature inside the auditorium is 25℃. So, air enters the evaporator tubing at outdoor temperature and leaves at the design temperature of conditioned space. Considering specific heat of air as 1 kJ/kg, the mass flow rate of air is obtained from the following equation.

$$Q = m_a c_p \Delta T \tag{1}$$

Here, Q = heat transfer rate, ΔT = temperature difference of air, m_a = mass flow rate of air, c_p = specific heat of air. From equation (1), the mass flow rate of air is found as, 38.68 Kg/s. Since ammonia is chosen as refrigerant, copper made tubes can't be used in this design because ammonia reacts chemically with copper or copper-based alloys. So, heat exchangers are designed with aluminum tubes.

To design this heat exchanger, logarithmic mean temperature difference (LMTD) method is used and the following factors are assumed. Firstly, the overall heat transfer coefficient (U) of the heat exchanger is constant. Secondly, the specific heat and mass flow rate of air and refrigerant are constant. Thirdly, the flow conditions are steady. Finally, the exchanger system is properly insulated and heat loss is negligible.

Now, the overall heat transfer coefficient for aluminum made tube in tube heat exchanger is 1200 W/m^2℃ but, this value can't be used directly to determine the dimensions of evaporator because, when air flows over aluminum tubes, a layer of dust is created which reduces heat transfer rate. Fouling factor (R_f) plays an important role here to obtain the correct dimensions. For air, the fouling factor is 0·00009 m^2k/W. Now, the equation of the fouling factor is,

$$R_f = \frac{1}{U_{dirty}} - \frac{1}{U_{clean}} \tag{2}$$

Here, U_{dirty} and U_{clean} represent the overall heat transfer coefficients of dirty and clean heat exchangers respectively. From equation (2), the actual overall heat transfer coefficient is 1083·03 W/m^2℃. Now, considering a counter flow heat exchanger, the equation of log mean temperature difference is,

$$LMTD = \frac{(T_{h2} - T_{c2}) - (T_{h1} - T_{c1})}{\ln[\frac{T_{h2} - T_{c2}}{T_{h1} - T_{c1}}]} \tag{3}$$

Where, T_{h1} = inlet temperature of air, T_{h2} = outlet temperature of air, T_{c1} = inlet temperature of refrigerant, T_{c1} = outlet temperature of refrigerant. The temperature of the cold fluid (refrigerant) has not changed since evaporation takes place at a constant temperature (14℃). From equation (3), the logarithmic mean temperature difference is 17.05℃. The total surface area of evaporator tubing is calculated from the following equation,

$$Q = U_{dirty} A (LMTD) \tag{4}$$

From equation (4), the total surface area of evaporator tubing is 29.33 m^2. Assuming, tube diameter as 10 cm, tube length becomes 102.12 m.

Design of Compressor

Considering, condensing temperature as 48.9℃ and evaporating temperature as 14℃, from Mollier chart of ammonia, it is found that for this 14℃ temperature, temperature line cuts saturated vapor curve at 0.62 MPa and for 48.9℃ temperature, relevant pressure is 2 MPa. These pressures are suction and delivery pressures of compressor respectively. So, the pressure ratio of the compressor is 3.225.

Now, the amount of heat absorbed by evaporating refrigerant molecules is equal to the cooling load of the auditorium. At 14°C latent heat of evaporation of ammonia is 1210 kJ/kg. The mass flow rate of ammonia is obtained from the following equation.

$$Q = m_r L_v \tag{5}$$

Here, m_r = mass flow rate of refrigerant, L_v = latent heat of evaporation of the refrigerant. From equation (5), the mass flow rate of ammonia is 0.45 kg/s. The power required to operate the compressor is calculated from the following equation.

$$P = \frac{\gamma q\, p_1}{(\gamma-1)}\left[\left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] \tag{6}$$

Here, p_1 = suction pressure, p_2 = delivery pressure, q = volume flow rate, γ = specific heat capacity ratio. Since, the density of ammonia is 0.73 Kg/m^3, the volume flow rate is obtained as, 0.616 m^3/s. Using the specific heat capacity ratio of ammonia as 1.32, from equation (6), the required power is obtained as 517.1 kW.

Design of Condenser

Ammonia vapor is drawn to the condenser from the compressor at 48.9℃. At this temperature, the latent heat of condensation is 1055 kJ/kg. In the condenser, ammonia vapor releases heat and returns to the liquid phase. From equation (5), the rate at which heat is released by refrigerant during the condensation process is obtained as 475.75 kJ/s. In this design, a water-cooled condenser is used. So, cooling water will absorb heat from hot refrigerant at the same rate. The temperature of the water entering the condenser is equal to the outdoor temperature (39°C) and water outlet temperature is assumed as, 46°C. Since the specific heat of water is 4·184 kJ/kg, the mass flow rate of water becomes 16.26 kg/s from equation (1). The actual overall heat transfer coefficient for the condenser is the same as the evaporator. Now, putting these values in equation (3), the logarithmic mean temperature difference for the condenser comes out as 5.814℃. Similarly, from equation (4), the surface area of the evaporator is found out as, 87.13 m^2. Assuming tube diameter as 10cm, length of condenser tubing becomes 277.36 m.

COP of Vapor Compression System

The coefficient of performance of the vapor compression cycle is the ratio of cooling load and compressor work. In this calculation, the cooling load is 541.6 KW and the amount of power consumed by the compressor is 517.1 KW. As a result, the coefficient of performance becomes 1.05.

3. Design of the Main Components of Vapor Absorption System

In this design, a single effect vapor absorption cycle is considered without any refrigerant heat exchanger for simplicity and cost reduction. The concentration of ammonia in the refrigerant, strong solution, and weak solution are kept as 0.98, 0.42, and 0.38 respectively [4]. Condensing and evaporating temperatures are kept similar to the previous system. Concentration, enthalpy, temperature and other properties of every state point are calculated below to make a complete design.

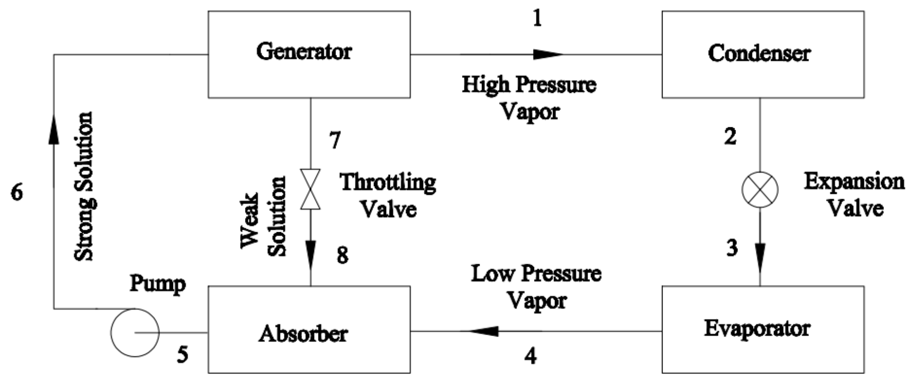

Fig. 1. Main components of vapor absorption system

Determination of the Mass Flow Rates

To determine the mass flow rates of refrigerant, absorbent and solution, properties of state point two, state point three and state point four are needed to know. At state point two, temperature and concentration of the refrigerant stay at 48.9 ℃ and 0.98 respectively. From the concentration-enthalpy diagram of ammonia, at this point, pressures of refrigerant is 19.98 bar and enthalpy of refrigerant is 220 kJ/kg. Condensed refrigerant reaches state point three through the expansion valve and expansion takes place at constant enthalpy. So, enthalpy of state point three is the same as state point two however, the pressure of refrigerant drops down. Now, the evaporating temperature is considered as 14℃ and liquid ammonia starts to get vaporized when it crosses state point three and enters the evaporator tubing. The concentration of ammonia remains unchanged in this process. From the concentration-enthalpy diagram of ammonia, the pressure of the refrigerant at state point three is 7.1 bar. At state point four, the refrigerant gets completely evaporated. Temperature, pressure, and concentration of refrigerant remain unchanged in this process. From the vapor solution portion of the concentration-enthalpy diagram, enthalpy of refrigerant is 1250 kJ/kg. Now, the mass flow rate of refrigerant is calculated from the following equation.

$$Q = m_r(h_4 - h_3) \tag{7}$$

Where, Q = heat flow rate, m_r = mass flow rate of refrigerant, h_3 = enthalpy at state point three, h_3 = enthalpy at state point four. From equation (7), the mass flow rate of refrigerant is .52 kg/s. Since the total mass of ammonia is constant, the total mass of ammonia in solution would be the same as the summation of the masses of ammonia in the refrigerant vapor and water. So, the mass balance equation can be written as,

$$m_s X_s = m_r X_r + m_w X_w \tag{8}$$

Here, m_s = mass flow rater of solution, m_r = mass flow rate of refrigerant, m_w = mass flow rate of water, X_s, = concentration of ammonia in the solution, X_r = concentration of ammonia in the refrigerant, X_w = concentration of ammonia in the water. The total mass of the solution is equal to the summation of the masses of absorbent and refrigerant. So, the following equation can be written.

$$m_s = m_r + m_w \tag{9}$$

Solving equation (8) and (9), mass flow rate of absorbent and solution are obtained as 7.362 kg/s and 7.89 kg/s respectively.

Design of Evaporator

The design of the evaporator for the vapor absorption system is completely the same as the vapor compression system.

Design of Condenser

Properties of state point one is needed to know to accomplish the design of condenser. This design procedure is quite similar to the previous system. At this state point, the saturated vapor of ammonia enters the condenser from the vapor generator. At this state point, temperature, pressure and concentration of refrigerant are the same as state point two because condensation takes place at constant pressure and temperature. From the concentration enthalpy diagram, enthalpy of vapor refrigerant which is at equilibrium with this liquid solution, is 1300 kJ/kg. The amount of heat rejected by the condenser is calculated by the following equation.

$$Q = m_r(h_1 - h_2) \tag{10}$$

Here, h_1 = enthalpy at state point one, h_2 = enthalpy at state point two. From equation (10), heat rejected by condenser during the condensation period is calculated as 568.08 KW. Considering the inlet temperature of the condenser cooling water is the same as the outdoor temperature (39℃) and assuming, water outlet temperature is 46℃, the mass flow rate of water can be calculated. Since, the specific heat of water is 4·184 kJ/kg, from equation (1), the mass flow rate of water is 19.39 kg/s. The value of the actual overall heat transfer coefficient for the condenser tubing of this system is the same as the vapor compressor system (1083·03 W/m^2). Since, the condensing temperature is 48.9℃, from equation (3), the logarithmic mean temperature difference is obtained as, 5.814℃. Using these values, the dimensions of the condenser are calculated. From equation (4), the heat exchanging area of the condenser is 90.22m^2. Assuming tube diameter as 10cm, tube length is found as 287.17 m.

Design of Generator

In the aqua ammonia absorption generator, heat is added from an external source to boil off the ammonia from the solution. Then, the remaining weak solution is drawn to the absorber where it absorbs the ammonia vapor, coming from the evaporator. As a result, the solution gets strong and drawn to the generator by a pump. Complete properties of state point five, six and seven are needed to know to design the generator.

The strong saturated solution enters the pump through state point five. Pressure remains similar to the state point four and concentration of ammonia becomes 0.42 (reference value). From the concentration-enthalpy diagram, temperature and enthalpy of the solution are 65℃ and 45 kJ/kg respectively. Pump work is neglected in this calculation. Through sate point six, the pressurized strong solution enters the generator and pressure is raised by the pump as the same as the pressure of state point one (19.98 bar). Neglecting pump work, enthalpy of solution is equal to enthalpy at state point five. At state point seven, the weak solution leaves the generator and pressure doesn't change. As a result pressure and concentration become 19.98 bar and 0.38 respectively. From the concentration-enthalpy diagram, enthalpy of this solution is 295 kJ/kg. Similarly, the temperature of the solution becomes 115 ℃.

Now, the weak solution enters the generator through state point six. After the heating up process, generated vapor leaves the generator through state point one and the remaining solution becomes weak. Then the weak solution leaves the generator through state point seven. Using the energy balance equation,

$$Q_G = m_r\, h_1 + m_w\, h_7 - m_s\, h_6 \tag{11}$$

In this equation, Q_G = the amount of heat needed to supply to run the vapor generator. From equation (11), the amount of heat added during this process is 2500.54 kW.

Design of Absorber

The absorber is needed to cool down so that, low-pressure ammonia vapor can be dissolved through the weak solution to make the solution strong again. The strong solution leaves the absorber through state point five. Applying the energy balance equation in the absorber,

$$Q_A = m_w\, h_8 + m_r\, h_4 - m_s\, h_5 \tag{12}$$

Here, Q_A = the amount of heat absorbed during this process. From equation (12), the amount of heat absorbed during this process is 2474.24 kW

A throttling valve works to reduce the pressure of the weak solution, which comes out from the generator. The pressure is reduced to 7.1 bar. As a result, low-pressure ammonia vapor can reach the absorber through state point eight and makes the solution strong again.

COP of the Vapor Absorption System

The coefficient of performance of vapor absorption refrigeration cycle is the ratio of cooling load and the amount of heat supplied to the generator. In this calculation, the cooling load is 541.6 kW and 2500 kW heat is supplied to the generator. As a result, the coefficient of performance becomes 0.217.

4. Cost Analysis

A complete comparison between the two proposed systems cannot be made without a cost analysis. In the estimation of Elsafty [5], a cast analysis is shown for different air conditioning systems in terms of the equivalent annual cost. The maintenance cost of these systems is neglected because maintenance is an uncertain process and no exact formula can be provided to forecast maintenance costs accurately.

From different online market sources, it is observed that water-cooled vapor compression chillers cost around \$400 per tonnage. So, total present value, for a chiller of 154 TR capacity would be, \$61600. Vapor absorption chillers cost much higher than vapor compression chillers. A typical aqua ammonia chiller costs around \$1540 (€1400) per tonnage [6]. For the auditorium, this figure would be \$237160. The equivalent annual costs of both of these systems is determined by the following formulas.

$$EAC = \frac{\text{Net present value}}{A_{t,r}} \tag{13}$$

$$A_{t,r} = \frac{1-\frac{1}{(1+r)^t}}{\mathrm{r}} \tag{14}$$

Where, EAC = equivalent annual cost, $A_{t,r}$ = annuity factor, r = interest rate, t = expected lifespan. Since, the expected lifespan of these systems is considered as 20 years and the benchmark interest rate of the banks of Bangladesh is almost 6% at this moment. From equation (14), the annuity factor becomes 11.47. Operating costs are calculated in terms of the power consumption rate. Assuming, average usage of the auditorium stays nearly forty hours, a monthly and then a yearly power consumption rate is calculated. The efficiency of typical vapor compressors is taken under consideration to obtain the accurate power consumption rate. For ammonia compressor with pressure ratio 3.225, isentropic efficiency is 84% [7]. So, the actual power required to run the compressor is 615.6 kW. As a result, the monthly power consumption rate would be, 24,624 kW hours. For monthly usage above, 600 kW hours, the tariff is \$0.13 (BDT10.70) per kW hour. Consequently, the annual operating cost of the vapor compression system becomes \$37940. For the vapor absorption system, operating cost can be determined by the fuel consumption rate of the vapor generator. Natural gas is chosen as the fuel to heat the generator. Considering calorific value (52,300 kJ/Kg) and density (0.63 kg/m^3 at the supply pressure) of natural gas along with the power consumption rate of the generator (2500 kW), yearly gas usage of natural gas becomes 131,112m^3. Since the average efficiency of natural gas-operated vapor absorption generator stays nearly 40% [8], and the current supply price of natural gas is \$0.09 (TK7.39) per cubic meter in Bangladesh, operating cost of vapor absorption generator becomes \$29,068 per year. Using all of this information, a cost analysis is made and presented in the following table.

Table 1. Results of cost analysis

Considered Factors	Vapor Absorption System	Vapor Compression System
Cost of the main components ($)	237,160	61,600
Life span (years)	20	20
Annual interest rate (%)	6	6
Annuity factor	11.47	11.47
EAC for the main components ($/year)	20,677	5,371
Annual operating cost ($)	29,068	37,940
Total EAC ($)	**49,745**	**43,311**

From the previous calculations it is observed that in terms of equivalent annual cost, the vapor compression system is more suitable than the vapor absorption system. The summary of cost analysis is shown in a bar graph in figure 2.

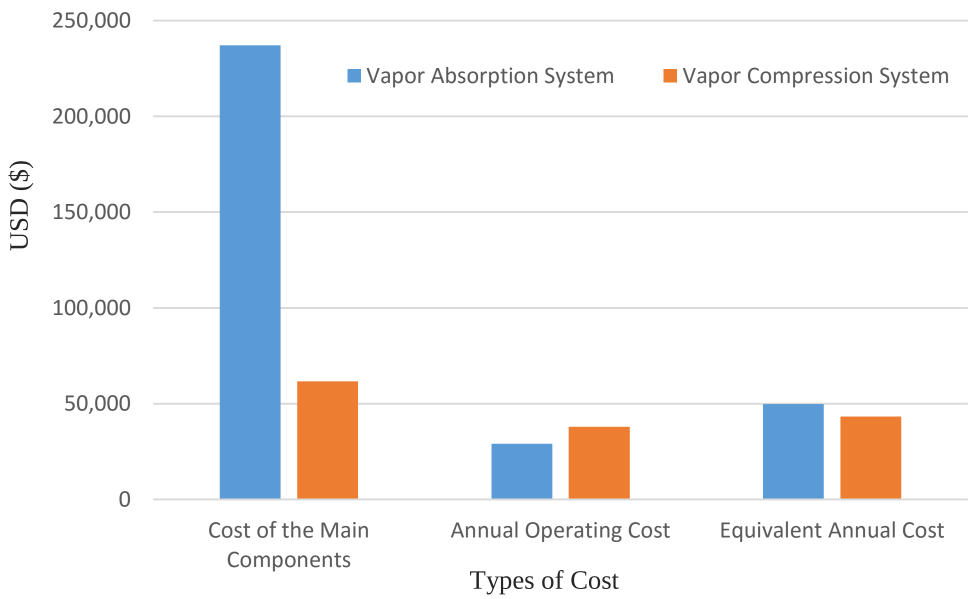

Fig. 2. Cost comparison between vapor compression and vapor absorption systems

5. Conclusion

The coefficient of performance of the vapor compression system is a bit higher than the vapor absorption system. Though the operating cost of the vapor absorption system is nearly 30% lower than the vapor compression system, it's installation cost is 74% higher. Overall, in terms of equivalent annual cost, the vapor compression system costs 14% less than the vapor absorption system. As a result, it is clear that, for the central air conditioning system of RUET auditorium, the vapor compression system would be much more efficient and cost-effective than the vapor absorption system.

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