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# Thermal Design and Performance Comparison of Water and Air-cooled Ammonia Condensers for Refrigeration Systems

KEYWORDS: Ammonia,Water-cooled condenser, Air-cooled condenser, HTRI

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**ABSTRACT** *In vapour compression cycle, ammonia vapours are compressed to its superheated state and condensed to liquid. Water and Air are mainly used as a cooling medium for ammonia condensation. In this paper the comparison between design and performance of a water-cooled and an air-cooled condenser has been carried out. Both the condensers have been designed manually as well as with HTRI software. Based on the fixed and operating cost it has been observed that, fixed cost of the water-cooled condenser is lower than that of air-cooled condenser. So an air-cooler is less economically attractive than a water cooler in this service. But nowadays, water has become a scarce and depleting resource. Considering the conservation of natural resources, air-cooled condensers may prove to be beneficial. Air-cooled condensers can be used in areas where water costs are excessive or where water availability is a problem.*

## Introduction

Ammonia is widely used in the refrigeration industry as a refrigerant. In vapour-compression cycle of refrigeration, ammonia vapours are compressed to its superheated state and condensed to liquid. Water and air are mainly used as a cooling medium in most of the operations. The debate of water versus air cooling has been going on for long. The choice of cooling medium depends on various factors such as location, weather conditions, space, fouling, cleaning, thermal pollution and shortage of makeup water and capital cost. Other factors that also affect the selection are fixed cost, maintenance and operating cost of the coolers and surface area [1, 2, 3]. Installation cost of an air-cooled condenser is almost double than that of a water-cooled condenser [1]. But, maintenance cost for air coolers are about 20-30% less than water cooled system [1]. Operating cost of air cooler is also less than water cooler. Operating cost in water coolers constitutes cost of raw water, make-up water for cooling tower, pumping and circulation cost and cooling tower maintenance etc. On the other hand operating cost of air coolers includes cost of power consumed by fan only [1, 2].

This paper focuses on the comparison between design and performance of a water-cooled and an air-cooled condenser for ammonia condensation. Both the condensers have been designed manually as well as with HTRI. A comparative analysis of both the results has also been carried out. The quantitative differences have been critically reviewed and argued. This paper discusses about the design considerations and design steps for both the condensers. Cost estimation based on the condenser dry weight has also been given for both the cases.

## Design of Water-cooled condenser

A case study has been taken up using Ammonia-Water system. In this case study the condenser has been designed manually (thermal and mechanical design) as well as by HTRI Xist. Superheated Ammonia vapours are to be condensed and water is used as a coolant.

**Case Study-I:** Superheated Ammonia vapours (at 120°Cand a pressure of 16.435 bars (absolute)) enter the shell side of a shell and tube heat exchanger and condense at 42°C. Cooling water is used as a cooling medium on tube side of the exchanger. Inlet and outlet temperatures of cooling water are 32°Cand 38°Crespectively. Circulation rate of ammonia is 0.6841 kg/s. Material of construction is assumed to be SS 304.

### 1.1 Design considerations

For designing the water-cooled condenser, some points such as fluid allocation, tube layout and passes, baffle type etc. have been considered. TEMA AES type exchanger has been selected. E-shell is the simplest in construction and also cheapest as compared to other shell types [4]. Water is routed through the tube side because it is more corrosive and fouling. Ammonia has been routed through shell side.

1.1.1 Optimization of number of tube passes:For selection of tube passes, a parametric study has been carried out. The design has been carried out for 2, 4, 6 and 8 passes. To avoid fouling, the tube side velocity should be kept greater than 1 m/s and less than 2m/s. At 2 and 4 passes, the tube side velocity comes out to be less than 1 m/s. And at 8 passes, it comes out to be more than 2 m/s. Based on the study, 6 tube passes have been selected as it gives optimum values of velocity, tube side pressure drop and % overdesign.

1.1.2 Selection of tube layout:For selection of tube layout, a parametric study has been carried out. The design has been carried out for 30o, 45o, 60oand 90olayout. Ammonia service is corrosive and would require continuous cleaning lanes. Cleaning lanes can only be accommodated in square layout. So, a square tube layout of 45ohas been selected as it gives optimum number of tubes and optimum value of % overdesign.

1.1.3 Optimization of baffle spacing:Single segmental baffles have been selected for the design. Double segmental baffles or No tubes-in-window (NTIW) baffles can also be selected, but they give a slightly lower value of heat transfer coefficient and, % overdesign is also decreased[5, 6]. For selection of baffle spacing, a parametric study has been carried out. The design has been carried out for 200, 250, 300, 350 mm spacing. Condenser handles vapors, so the possibility of flow-induced vibration is very high. So in order to eliminate the problem of vibration in the above design, baffles have been placed more closely. A baffle spacing of 250 mm has been selected, as it gives optimum values of B-stream flow fraction, shell side pressure drop and % overdesign.

### 1.2 Thermal Design (Manual)

For manual design of Water-cooled condenser, standard correlations based on Kern's method have been used. All the

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necessary data have been taken from relevant literatures. The first step in the design is the fluid allocation. Next step is heat duty (for desuperheating and condensing separately) and water flow-rate calculation. The physical properties have been generated based on the standard co-relations from Perry's Chemical Engineers' Handbook, 8th Edition.For calculation of mean temperature difference for desuperheating and condensation, intermediate temperature based on condensation duty has been calculated. Area required, number of tubes, shell diameter, shell side and tube side heat transfer coefficients and overall coefficients have been calculated. It is important to note that, shell side coefficient and overall coefficient have been calculated separately for desuperheating and condensation. Based on overall coefficient, area provided and % overdesign has been calculated. Shell side and tube side pressure drop has been calculated at last [3]. The process design summary is given in Table 1.

**1.3 Mechanical Design and Cost Estimation**
Mechanical designof the condenser includes design of shell, tubes, front and rear heads, channel shell, tubesheet, flanges, nozzle pipes and nozzle flanges etc. These are calculated using design codes such as ASME, TEMA standards and IS 4503. Based on the mechanical design carried out for water-cooled condenser, approximate weight of the condenser has been estimated as 3800 kg (approx.) [6, 7].

Based on the approximate weight, fixed cost has been estimated. The cost has been estimated based on only the dry weight of the condenser. According to World Steel Prices, the approximate cost of SS-304/kg is Rs163.34/-. Weight of the condenser is 3800 kg. Estimated cost of condenser is Rs6,20,692/-.Cost of providing cooling water to the condenser can be calculated based on cooling water cost of Rs1.45/1000 liter [8]. Cooling water flow rate is 1,22,390liter/hr. Hence, cost of cooling water is Rs177.45/hr.

**1.4 Thermal Design (HTRI)**
To carry out a comparative analysis, water-cooled condenser has been designed in HTRI software. All the geometrical parameters have been kept same as in the Manual design. For generating the fluid properties in HTRI, 'Component by Component' method is used. Ammonia and Cooling Water are selected from the database as the hot and cold fluid respectively.

**2.5Comparative analysis of Manual design and HTRI design**
Based on the 'Output Summary' and 'Final Results' obtained from HTRI the comparative analysis has been carried out between the Manual design results and HTRI results, which have been shown in Table 1.

**Table 1.Comparative analysis of Manual design and HTRI design**

| Parameters | Manual Design | HTRI Design |
|---|---|---|
| Type of Exchanger | TEMA AES | TEMA AES |
| Shell ID, mm | 840 | 840 |
| No. of shell side passes | 1 | 1 |
| No. of Tubes | 776 | 742 |
| Heat transfer area, m² | 119.86 | 129.945 |
| Heat Duty, kW | 896.05 | 861.2 |
| % Overdesign | 16.03 % | 14.81 % |
| Weight of Exchanger, kg | 3800 | 5383 |
| Cost Estimation, ` | 6, 20, 692 | 8, 79, 260 |
| Shell side | | |
| Velocity, m/s | 1.9 | 0.55 |
| Pressure drop ΔP, kPa | 1.391 | 2.67 |
| Heat transfer coefficient (Desuperheating), W/m²°C | 174.37 | 3787.62 |
| Heat transfer coefficient (Condensation), W/m²°C | 11372.23 | |
| Tube side | | |
| Velocity, m/s | 1.35 | 1.4 |
| Pressure drop ΔP, kPa | 45.06 | 46.37 |
| Heat transfer coefficient, W/m²°C | 6307.03 | 6696.02 |
| Overall heat transfer coefficient, W/m²°C | | |
| Desuperheating | 155.3 | 1003.87 |
| Condensation | 1200.62 | |

Based on the comparative analysis of both the manual design and HTRI design, following observations have been made. Almost all the parameters in HTRI design are matching with the parameters obtained in manual design. Some parameters that show deviation have been critically reviewed and discussed below:

**a. Heat duty:** Heat duty in manual design and HTRI design is not matching. Heat duty obtained in manual design is 896.05 kW, whereas duty in HTRI design is 861.2 kW. The reason for this difference may be that HTRI calculates the specific heat value of Ammonia at its critical conditions and then interpolates the values.

**b. Number of tubes:** Number of tubes obtained in manual design are 776, whereas number of tubes obtained in HTRI are 750. Unlike manual design, HTRI considers the mechanical clearances. Due to this reason, HTRI accommodates lesser number of tubes in a square layout.

**c. Baffle spacing:** Single segmental baffles with 250 mm baffle spacing have been selected. As per design guidelines, the baffle spacing in condensation should be kept equal to the shell diameter. But the condenser is handling vapours, so the possibility of flow-induced vibration is very high. So in order to eliminate the problem of vibration in the above design, baffles have been placed more closely at a distance of 250 mm from each other. Double segmental baffles or No-tubes-in-window (NTIW) baffles can also be selected but they give a slightly lower value of heat transfer coefficient and % overdesign is also decreased.

**d. Shell side pressure drop:** The shell side pressure drop obtained in manual design is 1.391 kPa, whereas pressure drop obtained in HTRI is 2.67 kPa which is very low. But as the heat transfer is taking place through condensation, there is no need of having a very high pressure drop. Moreover, a high pressure drop would lower the equilibrium condensing temperature and hence it would reduce the temperature driving potential. This would lead to an increase in required surface area.

**e. Impingement plate:** A circular impingement plate has been provided in HTRI design, whereas there is no such provision in manual design. Impingement plate prevents tube erosion from suspended condensate droplets and also prevents tube vibrations due to the entrance velocity of vapours.

**Design of Air-cooled condenser**
A case study has been taken up using Ammonia-Air system. In this case study, the condenser has been designed manually (thermal and fan power consumption) as well as by HTRI. Ammonia vapors are to be condensed using air as a cooling medium.

**Case Study-II:**Ambient air at 45°Cis used in a condenser while Ammonia is condensed at 60°C. Ammonia vapors enter the condenser at a temperature of 120°Cand a pressure of 26.3 bars (absolute) with a circulation rate of 0.6841 kg/s. Material of construction is assumed to be SS 304.

**2.1 Thermal design (Manual)**
For manual design of Air-cooled condenser, standard correlations have been used. All the necessary data have been taken from relevant literatures. The first step in the design is calculation of heat duty and air-flow rate. The physical properties have been generated based on the standard co-

relations from Perry's Chemical Engineers' Handbook, 8th Edition.Mean temperature difference, fin area, bare-tube area, wetted perimeter, equivalent diameter and number of tubes have been calculated. Dirty fin side heat transfer coefficient for 100 % fin efficiency and actual efficiency has been calculated. Tube side heat transfer coefficient and overall coefficient have been calculated. The inside heat transfer area required, heat transfer area provided, and % excess area have been determined. Outside and tube side pressure drop have been calculated at last [3]. The process design summary is given in Table 2.

**2.2 Fan Power Consumption and Cost Estimation**

For estimating the operating cost of an air cooled heat exchanger, fan power consumption has to be calculated. For calculating the fan power consumption, few parameters are required such as face velocity, pressure drop across bundles, fan efficiency and bundle area. A typical face velocity for the air flowing across the tube bundle is 2.5 to 3 m/s.

**Fan power consumption can be estimated as follows [8]:**

Here,the face velocity ($u_f$) is 2.95 m/s.Pressure drop across bundle ($\Delta P_b$) is 1758.0105 N/m$^2$. Fan efficiency ($\eta_f$) in this case is 0.65 and the bundle area ($A_b$) for 70 tubes per bank is 9.03 m$^2$. So, using all the above values $P_f$ is calculated as 72.05 kW. Allowing for motor efficiency of 95 % total power consumed $P_f$ comes out to be 68.45 kW.

Operating cost of air-cooled exchanger can be determined by calculating the fan power consumption. The operating cost of running an air-cooled condenser is typically 0.06 $/kWh [8]. So, operating cost of running this air-cooled condenser is Rs224.32/hr.

**2.3 Thermal Design (HTRI)**

To carry out a comparative analysis, the air-cooled condenser has been designed in HTRI software. All the geometrical parameters have been kept same as in the Manual design. Ammonia is allocated to tube side as the outer side is ambientair. For generating the fluid properties in HTRI, 'Component by Component' method is used. Ammonia is selected from the database as the hot fluid. Forced draft cooler is selected in HTRI. As the condenser is forced draft, the type of fin selected is High fin. Other parameters such as number of passes, number of rows and tube count are calculated in HTRI.

**2.4 Comparative analysis of Manual design and HTRI design**

Based on the 'Output Summary' and 'Final Results' obtained from HTRI a comparative analysis has been carried out between the Manual design results and HTRI results, which have been shown in Table 2. It was noted that almost all the parameters in HTRI design are matching with the parameters obtained in manual design.

**Table 2.Comparative analysis of Manual design and HTRI design**

| Parameters | Manual Design | HTRI Design |
|---|---|---|
| Tube length, mm | 3000 | 3000 |
| Total number of finned tubes | 700 | 700 |
| Number of banks | 10 | 10 |
| Tube pitch, mm | 43 (Equilateral triangular) | 43 (Equilateral triangular) |
| No. of tube passes | 4 | 4 |
| Fin type | Spiral wound transverse fin | High fin |
| No. of fins per inch | 8 | 8 |
| Fin efficiency % | 65 | 65 |
| Heat duty, kW | 783.15 | 782 |
| Total outside heat transfer area, m$^2$ | 1213.695 | 1215.93 |
| Tube Side Heat transfer coefficient, W/m$^{2o}$C | 1136.67 | 1083.14 |
| Tube Side Velocity, m/s | 0.1842 | 0.21 |
| Tube Side Pressure drop, kPa | 0.3515 | 1.163 |
| Air side pressure drop, mm $H_2O$ | 179.26 | 29.4 |
| % Overdesign | 11.07 % | 13.04 % |
| Weight of Exchanger, kg | - | 9307 |
| Cost Estimation, ` | - | 15, 20, 205 |

**Results and Discussion**

Based on the designs of water-cooled and air-cooled condenser, it is seen that the cost of installing an air-cooled condenser in the given case study is higher. It is observed that, the operating cost for water-cooled condenser isRs177.45/hr and for air-cooled condenser it is Rs224.32/hr. The operating cost of Air-cooled condenser is also higher. But, operating cost in water coolers constitutes cost of raw water, make-up water for cooling tower, pumping and circulation cost and cooling tower maintenance etc. So, if all these cost heads are added up, then it is possible that air-cooled condenser might prove to be cheaper.

**Table 3.Cost comparison Water-cooled condenser and Air-cooled condenser**

| Cost comparison | | Water-cooled condenser | Air-cooled condenser |
|---|---|---|---|
| Weight of Condenser, kg | Manual Design | 3800 | - |
| | HTRI Design | 5382 | 9307 |
| Fixed cost, Rs | Manual Design | 620692 | - |
| | HTRI Design | 879260 | 1520205 |
| Operating cost, Rs/hr | | 177.45 | 224.32 |

**Conclusion**

The debate of water cooling versus air cooling seems to be never ending. Based on the fixed cost and operating cost it has been observed that, the fixed cost of the Water-cooled condenser is lower than that of Air-cooled condenser in this case. Cost of installing an Air-cooled condenser is almost double than that of a Water-cooled condenser. But based on the cost of raw water, make-up water, cooling tower maintenance and other operating costs, air cooled condensers may prove to be advantageous over water cooled condensers. As water resources are depleting rapidly, it is really important to conserve water. Also in many areas water has become a scarce and expensive commodity. Due to this reason, in spite of having a higher fixed cost, air cooled condensers may prove to be advantageous over water cooled condensers in the long run.

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