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Design and Numerical Analysis of a Combined-Flow Evaporative Condenser for Cold Storage Applications

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Abstract

Energy efficiency plays a vital role in reducing operating costs and improving the overall performance of industrial refrigeration and air-conditioning systems. Evaporative condensers offer significant potential for reducing condensing temperature and compressor energy consumption by utilizing the combined effects of air movement and water evaporation. The present study focuses on the design and analysis of an evaporative condenser while maintaining geometric similarity with real-scale equipment. The proposed condenser consists of a bundle of 300 stainless-steel tubes having an external diameter of 26.67 mm. The study includes the determination of major design parameters, development of the condenser geometry, and numerical simulation of its thermal and flow characteristics. The design methodology considers the heat rejection requirements, refrigerant-side and air-side conditions, water circulation, and heat and mass transfer processes associated with evaporative cooling. A three-dimensional computational model of the evaporative condenser is developed to evaluate the temperature distribution, airflow behavior, and thermal performance of the condenser. The simulation results provide insight into the interaction between the air, water spray, and tube bundle and help assess the effectiveness of the proposed configuration. The developed design and analysis methodology can serve as a basis for the optimization and development of energy-efficient evaporative condensers for industrial refrigeration applications.

1. Introduction

Refrigeration systems are widely used in food processing, pharmaceutical industries, cold-storage facilities and other industrial applications where controlled low-temperature conditions are required. A vapour-compression refrigeration system transfers heat from a low-temperature region to a high-temperature environment through the combined operation of the evaporator, compressor, condenser and expansion device. Among these components, the condenser plays a critical role because it rejects the heat absorbed by the refrigerant in the evaporator together

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with the heat equivalent to compressor work. The energy consumption of industrial refrigeration systems is strongly influenced by condensing conditions. An increase in condensing temperature generally increases compressor pressure ratio and consequently increases compressor power requirement. Therefore, improving condenser heat rejection can contribute to improved refrigeration-system efficiency. Conventional condensers are broadly classified as air-cooled, water-cooled and evaporative condensers. An evaporative condenser combines characteristics of a water-cooled condenser and cooling tower. In an evaporative condenser, water is sprayed over the external surface of refrigerant tubes while air is circulated across the wetted tube bundle. A small portion of the circulating water evaporates, and the associated latent heat transfer provides an effective mechanism for removing heat from the refrigerant. Combined-flow evaporative condensers employ both the condensing coil and fill surface. The reported design uses parallel flow of air and spray water over the coil and cross-flow interaction through the fill region. Such an arrangement can increase the interaction between air, water and the heat-transfer surfaces. Previous investigations have demonstrated the potential of evaporative condensers for refrigeration applications. Studies cited in the original project report have investigated condenser design, heat-transfer coefficients, CFD analysis and performance optimization of evaporative condenser configurations. Acunha Jr. et al. investigated a geometrically scaled evaporative condenser and identified de-superheating, condensation and subcooling regions. Patel and Shah investigated evaporative condenser optimization and highlighted the potential of evaporative cooling for reducing energy consumption. The objective of the present study is to develop a design methodology for a large-capacity combined-flow evaporative condenser suitable for cold-storage applications and to investigate its flow and thermal characteristics using CFD.

2. Literature Review

Karimi et al. reviewed different methods for condenser design for vapour-compression refrigeration systems. Nwasuka et al. investigated the design and performance evaluation of a condenser using R134a. Goswami and Babu investigated CFD and thermal characteristics of an air-cooled condenser using different fluids and materials. Shafiuddin et al. studied flow analysis of condenser fins using CFD. Dabhi and Thakore compared air-cooled, water-cooled and evaporative condenser configurations. Patel and Shah investigated evaporative condenser optimization and highlighted the potential of evaporative cooling for reducing energy consumption. Acunha Jr. et al. experimentally investigated a reduced-scale evaporative condenser with geometric similarity to full-scale equipment. R22 was used as the refrigerant and different water and air mass flow rates were considered. Three heat-transfer regions—de-superheating, condensation and subcooling—were identified. The literature indicates that evaporative condenser performance depends on refrigerant-side conditions, air flow, water flow, tube geometry, heat-transfer coefficients and ambient psychrometric conditions. Sagar Mushan et al. presented work focuses specifically on the design of a large-capacity combined-flow evaporative condenser for a cold-storage application, followed by CAD development and representative CFD analysis

3. Design Methodology

3.1 Design Conditions: The design of evaporative condenser is as follows.

Table 1. Design of combined flow evaporative condenser

Parameter	Value
Refrigeration capacity	463 TR
Refrigerant	R717 (Ammonia)
Refrigerant inlet temperature	100°C
Refrigerant outlet temperature	32°C
Refrigerant pressure	13.5 bar
Evaporation temperature	−2°C
Air inlet DBT	35°C
Air inlet WBT	28°C
Relative humidity	60%
Inlet water temperature	30°C
Outlet water temperature	33.5°C

3.2 Selection of Condenser Tube

SS304 was selected as the tube material. The selected tube dimensions are: outside diameter = 26.67 mm, inside diameter = 23.368 mm, wall thickness = 1.651 mm and thermal conductivity = 16.2 W/mK. The original report states a total tube length of approximately 1800 m for the selected condenser configuration.

3.3 Water Flow Rate

The water-side enthalpy difference is $\Delta h = 140 - 125.7 = 14.3$ kJ/kg.

Using $\dot{m}_w = Q/\Delta h_w$, the reported water circulation rate is $\dot{m}_w = 113.64$ kg/s.

4. Refrigerant-Side Heat Transfer

4.1 Refrigerant Mass Flow Rate

The reported ammonia enthalpies are $h_{in} = 1671.8$ kJ/kg and $h_{out} = 351.48$ kJ/kg. Hence, $\Delta h_r = 1320.32$ kJ/kg and $\dot{m}_r = Q/\Delta h_r = 1.24$ kg/s.

4.2 Refrigerant Velocity

The internal tube area based on the reported inside diameter is 428.65 mm². The original report calculates an inlet ammonia velocity of approximately 365.7 m/s.

4.3 Reynolds Number

Using the reported fluid properties, the Reynolds number for ammonia vapour was 5.28×10^6 and the saturated/liquid value was 0.5586×10^6. The reported average Reynolds number was 2.913×10^6, with an average Prandtl number of approximately 1.114.

4.4 Internal Heat-Transfer Coefficient

Using the reported Petukhov-based correlation, the friction factor was 9.766×10^{-3} and the Nusselt number was 3686.34. The resulting internal heat-transfer coefficient was h_i = 39,027.77 W/m²K.

5. External Heat Transfer

5.1 Tube Arrangement

The condenser tubes were arranged in a staggered configuration. The reported transverse pitch is 57.4 mm and longitudinal pitch is 50 mm. The water velocity over the external tube surface was reported as 0.464 m/s, with Reynolds number 15,445.34.

5.2 External Heat-Transfer Coefficient

Using the correlation reported in the project, the external heat-transfer coefficient was calculated as h_o = 1,722.89 W/m²K.

6. Overall Heat-Transfer Coefficient

The overall heat-transfer coefficient was determined by considering internal convection, tube-wall conduction and external convection. The project reports an overall heat-transfer coefficient of U = 1398.797 W/m²K. The original calculation should be rechecked for consistency between the resistance formulation, reference area and numerical value before submission.

7. Heat-Transfer Area

7.1 De-Superheating Section

The reported de-superheating heat-transfer area was 8.15 m², using an LMTD correction factor of 0.98.

7.2 Condensation Section

For the phase-change region, the reported arithmetic mean temperature difference was 2.425°C and the phase-change heat-transfer area was 330.28 m². Therefore, the total calculated heat-transfer area was A_{total} = 8.15 + 330.28 = 338.43 m². The design selected 300 tubes.

8. Air Flow Rate and Water Evaporation

The original design considered inlet air at 35°C DBT and 28°C WBT. The reported outlet air conditions were DBT = 37°C, WBT = 33.67°C and relative humidity = 80%. The calculated air mass flow rate was 52.04 kg/s and volumetric flow rate was 47.744 m^3/s. The reported water evaporation rate was 0.6739 kg/s.

9. CAD Modelling and Condenser Configuration

A three-dimensional model of the evaporative condenser was developed using 3DEXPERIENCE and subsequently imported into ANSYS Fluent for CFD analysis. The major components of the condenser assembly were an axial fan, outer casing, condenser coil and water-spray nozzles. The selected axial fan was specified at 4500 CFM and 1 HP. The outer casing dimensions were reported as 6200 × 3000 × 4500 mm with 5-mm stainless-steel construction. The condenser coil used SS304 tubes with 26.67-mm outside diameter and 23.368-mm inside diameter.

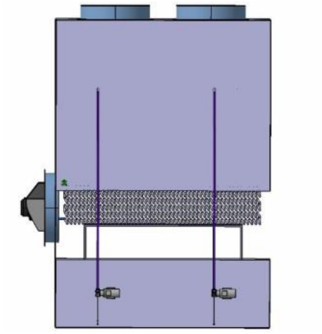

Figure 1. 3D assembly of combined-flow evaporative condenser

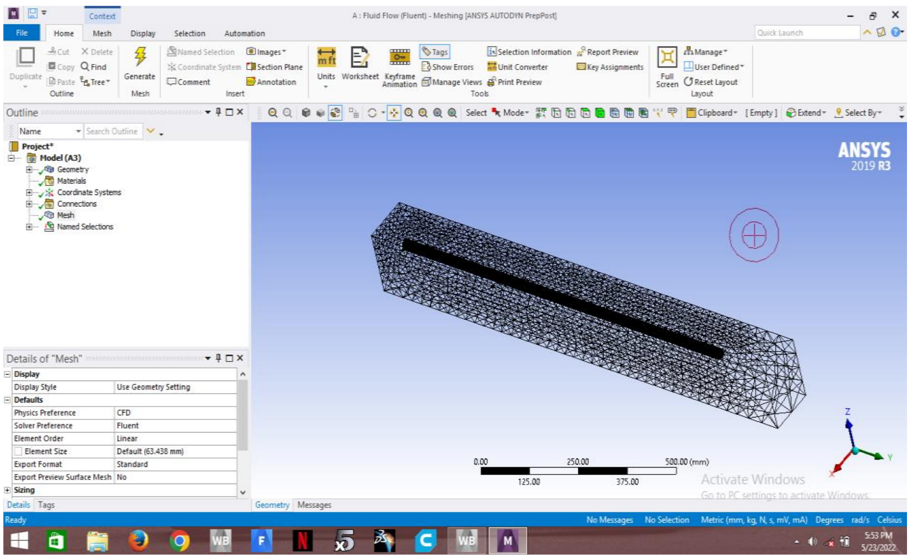

Figure 2. Meshing

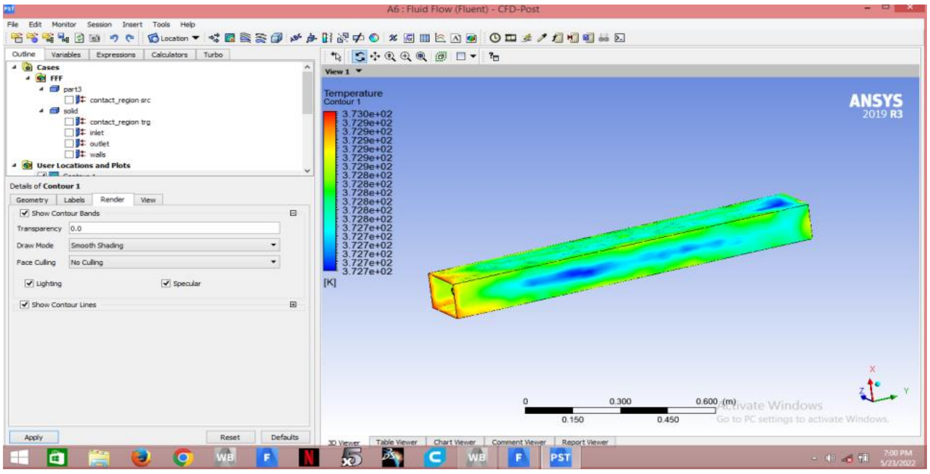

Figure 3. Temperature Contour

10. CFD Methodology

Because of the large physical dimensions of the complete condenser, the original study used a representative 1000-mm tube section for CFD analysis. The geometry was meshed using the ANSYS in-built mesher with tetrahedral elements. The simulation was run for 10 iterations. Temperature, pressure and velocity contours were obtained.

4. Results and discussion

The principal design results are as follows. The calculated results indicate that the external heat-transfer process provides a substantially lower heat-transfer coefficient than the refrigerant-side process. Consequently, the external wetted surface and air-water interaction are important to the thermal performance of the condenser

Table 2. Reported values for CFEC

Parameter	Reported value
Refrigeration capacity	463 TR
Heat rejection	≈1630 kW
Refrigerant	R717
Refrigerant mass flow rate	1.24 kg/s
Water circulation rate	113.64 kg/s
Water evaporation rate	0.6739 kg/s
Tube material	SS304
Tube outside diameter	26.67 mm
Tube inside diameter	23.368 mm

Number of tubes	300
Internal heat-transfer coefficient	39,027.77 W/m²K
External heat-transfer coefficient	1,722.89 W/m²K
Overall heat-transfer coefficient	1,398.80 W/m²K
Total heat-transfer area	338.43 m²
Calculated air mass flow rate	52.04 kg/s
Calculated air volume flow rate	47.744 m³/s

The design analysis demonstrates the feasibility of developing a large-capacity evaporative condenser using a 300-tube SS304 coil. The calculated heat-transfer area of 338.43 m² provides the basis for selecting the tube bundle. The design also incorporates air circulation and water spraying to exploit evaporative cooling. The calculated air-flow requirement is an important parameter because evaporative heat transfer is dependent on the psychrometric state of incoming air. The original calculation predicts an air mass flow rate of 52.04 kg/s and water evaporation rate of approximately 0.674 kg/s. The study also separates the condenser into de-superheating and condensation regions. The calculated areas were 8.15 m² and 330.28 m², respectively, indicating that the phase-change section dominates the required heat-transfer area. The CFD component complements the analytical design by providing temperature, pressure and velocity fields. Because the CFD analysis was conducted on a representative 1000-mm tube rather than the complete condenser, the numerical results should be interpreted as a local flow and thermal assessment rather than a full-system CFD prediction.

5. Conclusions

A combined-flow evaporative condenser was designed for a reported refrigeration capacity of 463 TR using ammonia (R717) as the refrigerant. The design conditions considered a refrigerant inlet temperature of 100°C, outlet temperature of approximately 32°C, and operating pressure of 13.5 bar. The selected condenser consists of 300 SS304 tubes with an outside diameter of 26.67 mm, inside diameter of 23.368 mm and wall thickness of 1.651 mm. The reported refrigerant mass flow rate is 1.24 kg/s, while the calculated water circulation rate is 113.64 kg/s. The reported internal and external heat-transfer coefficients are 39,027.77 W/m²K and 1,722.89 W/m²K, respectively. The total calculated heat-transfer area is 338.43 m², consisting of approximately 8.15 m² for de-superheating and 330.28 m² for the phase-change region. The calculated air mass flow rate is 52.04 kg/s and the reported water evaporation rate is 0.6739 kg/s. A three-dimensional CAD model was developed and representative CFD analysis was performed using a 1000-mm tube section. Temperature, pressure and velocity contours were obtained from the CFD model. Further work should include experimental validation of the complete condenser, quantitative CFD validation, investigation of different air and water flow rates, and optimization of tube arrangement and spray-water distribution

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