

A NUMERICAL SIMULATION ON HEAT TRANSFER CHARACTERISTICS IN THE CASCADE HEAT EXCHANGER OF A R134A/CO₂ REFRIGERATION SYSTEM

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Abstract. This study focused on the phase transition of two refrigerants CO₂ and R134a using the numerical simulation method. The COMSOL Multiphysics 5.3a software was used to 3D simulate CO₂ condensation and R134a evaporation of a double pipe heat exchanger in a cascade refrigeration system. The simulation results indicate the heat transfer characteristics including temperature field, quality vapor, density transition, and fluid flow characteristics including velocity and pressure also. The above results are very consistent with those obtained from experiments under the same conditions. In addition, when the evaporation temperature of R134a increases, the inlet temperature and the condensation temperature of CO₂ increase, respectively. Besides, the evaporation temperature of R134a increases from 3.6°C to 4.7°C while the CO₂ condensation temperature increases from 7.9°C to 9.7°C and the CO₂ inlet temperature increases from 58.8°C to 63.8°C correspondingly.

Keywords: Cascade heat exchanger, R134a/CO₂, double pipe, simulation, heat transfer characteristics.

1 INTRODUCTION

We knew that CO₂ is not only a gas with large reserves in nature but also capable of being utilized in refrigeration systems with many excellent heat transfer characteristics with the name of R744. The basic properties of this refrigerant are low critical temperatures, and high operating pressures, requiring the technology of processing equipment and pipelines to ensure safety for operators and equipment. To overcome that limitation, we can use a cascading refrigeration system with the CO₂ refrigerant operating at a low stage to ensure operation under the critical point. The potential for the development of CO₂ refrigerant is very desirable, in order to realize its full potential, we need to understand the heat transfer characteristics of refrigerants in heat exchangers. The numerical simulation method is one of the research methods that save system investment costs in practice is proposed.

Related to the numerical simulation studies on low-temperature refrigeration systems. Ravi et al. [1] investigated the numerical and experimental on the vapor absorption refrigeration system. Hu et al. [2] experimentally studied the heat transfer characteristics of plate-fin heat exchangers with the high-efficiency model two-phase flow boiling at low temperature. Wang et al. [3] developed a fin-and-tube heat exchanger using supercritical hydrogen to identify the relationships of gravity force, flow state, and inhibition of heat conduction on the heat transfer characteristics. Guo et al. [4] provided an understanding of the fundamental behavior of the boiling in the annular flow regime by the CFD model. Besides, Chen et al. [5] used the VOF model to study the condensing process of the FC-72 in a 1-mm hydraulic diameter rectangular microchannel.

In addition, a little of studies that simulated heat exchange characteristics in refrigeration systems using CO₂ had been performed. Zhanga et al. [6] investigated a

finned-tube CO₂ gas cooler. In this study, some parameters including the heat transfer characteristics, air velocity fields, the temperature distribution at a variety of operating conditions were simulated and analyzed by the CFD model. Yang et al. [7] used the steady-state lumped parameter technology to study the performance of a CO₂ transcritical heat pump system. In addition, Dang et al. [8] numerically investigated the gas cooler of a CO₂ air conditioning system to analyze the heat transfer characteristics such as the velocity field, the pressure drop, the temperature profile, and the heat transfer rate.

For the cascade refrigeration systems using R134a or CO₂ as a refrigerant, the studies were mainly based on theory or experimental verification. Particularly, Song et al. [9] developed a cascade heat pump system using CO₂/R134a in theory. Under different working conditions, they studied the characteristics of the R134a and CO₂ cycles, respectively. Besides, Sanz-Kock et al. [10] experimentally evaluated a cascade refrigeration plant using R134a/CO₂ which operated under low evaporation temperatures. They concentrated on the temperature difference in the cascade heat exchanger, cooling capacity, COP, and the discharge temperature of the compressor. Wantha [11] theoretically evaluated and validated the experiments on the heat transfer characteristics that focused on the COP, the pressure drop, the condensate temperature, the evaporation temperature of a double-pipe internal heat exchanger using R1234yf/R134a. Furthermore, Zhang et al. [12] studied a cascade refrigerant system using a couple of R1270 and R744. In addition, the thermodynamics of the R744/R717 cascade refrigeration system to determine the optimal design for the system were analyzed in [13,14] that comprised of superheating degree, the subcooling temperature, the evaporating temperature, the condensing temperature, and the cascade temperature difference.

Most studies have focused on simulating heat transfer

properties in traditional refrigeration cycles operating under transcritical cycles using CO₂, with a focus on clarifying parameters such as the temperature profile, velocity field, pressure drop, and heat transfer rate. On the other hand, studies experimentally validating models mainly exploit absorption refrigeration systems, cascade systems, and refrigeration systems operating at medium temperatures. Commonly used fluids such as R134a, CO₂, FC-72, R717, R1270, R1234yf, R290, etc. Besides, the main research parameters are mass flow rate of fluid, inlet temperature, quality vapor, and COP. To sum up, the numerical study of heat transfer characteristics for cascading cycles using R134a and CO₂ pairs is innovative, which is an advanced study in the study of two-phase fluid flow simulation.

2 METHODOLOGY

2.1 Structure design

The simulation model in this study is the double-pipe heat exchanger in the R134a/CO₂ cascade refrigeration system. The main parameters for making this model include: a total heat exchange surface area $F = 0.185 \text{ m}^2$, it consists of 2 interlocking copper tubes. The inner tube has a diameter of 4mm, the outer tube has a diameter of 8mm. The total length is 15m and is divided into two parallel sets. Each set is bent into 23.5 turns with a diameter of 100 mm per turn as shown in **Fig. 1**.

2.2 Structure design

To analyze the heat transfer and fluid flow properties, the following assumptions are made: the fluid is continuous, the heat transfer is stable, neglect radiant heat exchange. The main equations used in the research include the equation of continuity, the equation of momentum, and the equation of energy.

For k- ϵ model, the equations for turbulent flow were applied appropriately that expressed by:

$$\rho \frac{\partial k}{\partial t} + \rho u \cdot \nabla k = \nabla \cdot \left[\left(\mu + \frac{\mu_T}{\sigma_k} \right) \nabla k \right] + P_k - \rho \epsilon \quad (1)$$

$$P_k = \mu_T \left[\nabla u : (\nabla u + (\nabla u)^T) - \frac{2}{3} (\nabla \cdot u)^2 \right] - \frac{2}{3} \rho k \nabla \cdot u \quad (2)$$

$$\rho \frac{\partial \epsilon}{\partial t} + \rho u \cdot \nabla \epsilon = \nabla \cdot \left[\left(\mu + \frac{\mu_T}{\sigma_\epsilon} \right) \nabla \epsilon \right] + C_{\epsilon 1} \frac{\epsilon}{k} P_k - C_{\epsilon 2} \rho \frac{\epsilon^2}{k} \quad (3)$$

Where: t is the time (s); T is the absolute temperature (K); C_p is the specific heat at constant pressure, (kJ/kg.K); ϵ is the rate of viscous dissipation, (m^2/s^3); k is the turbulent kinetic energy, (J/kg).

Based on the input data from theoretical calculations, the parameters are included in the simulation as **Table 1**.

Table 1. The initial declared parameters for simulation

Fluid	Parameter	Value	Description
R134a	T_R134a	4 [degC]	Evaporation temperature
	m_R134a	0.0136 [kg/s]	Mass flow rate
	P_R134a	3.376 [bar]	Evaporation pressure

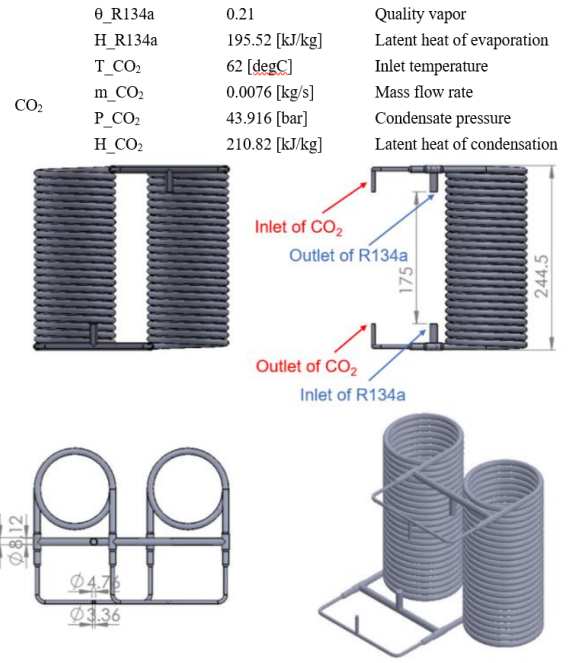


Fig. 1. Parameters design of the double pipe heat exchanger

3 RESULTS AND DISCUSSION

3.1 Temperature distribution

The temperature distribution at the CO₂ side and the R134a side is shown in **Fig. 2**. Obviously, the copper tube surface temperature on the R134a side gradually increases in proportion to the saturated liquid state after passing through the expansion valve and gradually increases to the superheated state. On the other hand, CO₂ gradually decreases the temperature from the slightly superheated state to the saturated state at the final segments of the heat exchanger. The simulation results show that: from the first 3 turns of the heat exchanger pipe section, the CO₂ fluid has a large temperature change from 64°C to 9.7°C (in the case of R134a evaporation temperature is 4.7°C). Starting from the 4th pipe section to the end of the heat exchanger while CO₂ begins to condense until the end of this process, the temperature is almost constant, completely consistent with the heat exchange principle of the counter-flow heat exchanger.

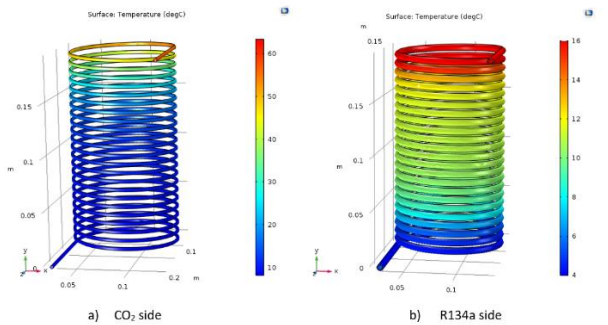


Fig. 2. Temperature distribution results from simulation

To study the influences of the evaporation temperature on the R134a side on the condensation temperature as well as the input temperature of CO₂, a series of evaporation temperature values were studied in the range from 3.6°C to

4.7°C. The results show that the inlet temperature of the heat exchanger also increases from 62°C to 64°C, respectively, while the condensate temperature increases from 90°C to 9.7°C. Basically, an increase in the evaporation temperature at the high stage means an increase in the condensation temperature at the low stage, resulting in an increase in pressure and the condensation temperature at the high stage leads to the above phenomena.

3.2 Quality vapor transition

The quality of vapor is a thermodynamic parameter that cannot be measured by experimental measuring devices. However, with 3D phase-change flow simulation, the quality vapor results are clearly shown in **Fig. 3** for both fluids. It indicates the phase transition upon evaporation of the R134a, specifically the phase change from the flash gas state with the quality vapor of 0.21 (blue part) to the vapor phase (red part). In the first three tube segments, the quality of vapor is equal to 1.0, the CO₂ fluid is in a nearly superheated state, then the fluid temperature decreases to transform the fluid from a slightly superheated state to a dry saturated vapor state. When the CO₂ temperature reaches the saturation temperature at the corresponding pressure, while the CO₂ temperature does not change, the quality of vapor begins to decrease from 1.0 to 0. The results in these cases also showed that the CO₂ fluid is completely condensed into a saturated liquid state.

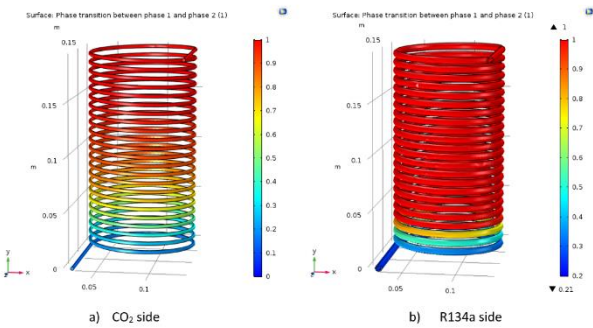


Fig. 3. Quality vapor transition process of CO₂ and R134a

3.3 Density transition

The density plays an especially key role to distinguish the fluid state and determine the phase transition zone in the heat exchanger. The simulation results in **Fig. 4**, show the density transition of the CO₂ and R134a sides.

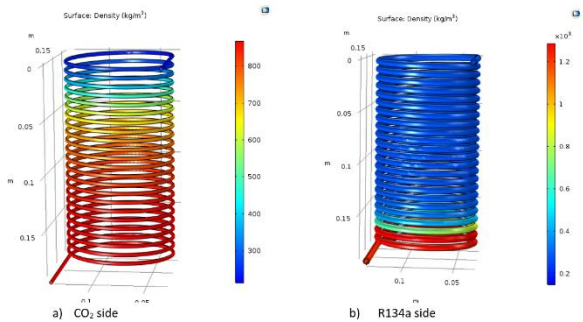


Fig. 4. Density transition process of CO₂ and R134a

At the CO₂ side, the initial fluid in the vapor state has a small density and in the liquid state has a large density. In

the vapor state, the mass is about 88.4 kg/m³ while in the liquid state, the density is about 868.4 kg/m³. At the R134a side, in the vapor state, the density has a value of about 16.55 kg/m³, while in the flash gas state, the density is about 1126.4 kg/m³. The simulation results of the density change process coincide with the simulation results of the quality vapor, particularly the density of the vapor phase is blue, and the density of the liquid phase is red. The above results are consistent with the physical characteristics of the refrigerants in the theoretical calculation.

3.4 Validating Simulation

To evaluate the reliability of the simulation model, the results of numerical simulation for the input temperature and condensation temperature of the CO₂ were compared to the experimental results in [15]. **Fig. 5** shows the relationship between condensation temperature and heat exchanger inlet temperature of the CO₂ refrigerant. The inlet temperature is in the range from 59°C to 64°C in simulation, and 58.8°C to 63.8°C in the experiment, while the condensation temperature is from 7.7°C to 9.7°C.

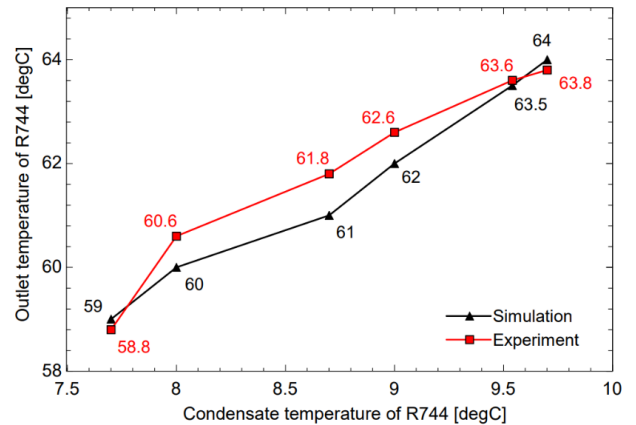


Fig. 5. The Comparison between the simulation and experiment of the Inlet temperature at the CO₂ side with a range of condensation temperature at R134a.

The outlet temperature of condenser obtained from the experiment is estimated to be the uncertainty values of 0.5% [16]. When the condensation temperature increases, the condensation pressure increases, which in turn increases the discharge temperature of the CO₂ compressor accordingly. From the results above, it indicates the similarities between the experimental results and the numerical simulation results. The error simulation is also in good agreement with the value of less than 10%.

4 CONCLUSION

With the aim of simulating the heat transfer properties of the cascade heat exchanger in the refrigeration systems using R134a/CO₂ pairs, the study has achieved the following results:

- This study figured out the properties of the R134a refrigerant when evaporating and the CO₂ refrigerant when condensing such as the temperature field, the quality of vapor, and the transition of density when the fluid performs evaporation or condensation. The above results were

inextricably linked.

- The study also showed that when the inlet temperature of the refrigerant R134a increases, the input temperature and condensation temperature of CO₂ also increase, specifically the evaporation temperature of R134a increases from 3.6°C to 4.7°C, the CO₂ condensation temperature increases from 7.9°C to 9.7°C and the CO₂ input temperature increases from 58.8°C to 63.8°C, which is consistent with the experimental results in the previous study.

- In addition, the results of the numerical simulation are quite consistent with the experimental data obtained in the previous study. The results are obtained with an error of less than 10% compared to the experimental results, which indicated that the results of the study were highly dependable.

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