Effect of cold fluid on supercritical heat transfer characteristics in conjugate cooling

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Abstract. The supercritical CO\textsubscript{2} conjugate cooling in double-pipe heat exchanger has been numerically investigated. The results of AKN turbulence model agree well with the experimental data. Compared to the wall condition assumption, the conjugate cooling condition is more suitable for supercritical CO\textsubscript{2} heat transfer simulation in double-pipe heat exchanger. For supercritical CO\textsubscript{2} conjugate cooling, the mixed convection is the most important factor. The influence of the cooling water temperature on the supercritical CO\textsubscript{2} conjugate cooling is more evident than the cooling water Re.

1. Introduction

As a natural non-toxic, non-combustible and inexpensive medium, CO\textsubscript{2} is critical pressure 7.38 MPa and critical temperature 31.2°C. Supercritical CO\textsubscript{2} is an ideal refrigerant, which has been used in air conditioners and heat pumps to replace traditional refrigerants that are harmful to the environment. Moreover, these thermal systems by CO\textsubscript{2} operate under supercritical conditions.

Research on supercritical fluid heat transfer has attracted worldwide attention. A large amount of experimental work has been carried out to research the supercritical fluid heat transfer. Both Cheng [1] and prioro [2] have reviewed the heat transfer characteristics of supercritical fluids. Dang [3] used three low-Re models to study the supercritical CO\textsubscript{2} heat transfer phenomenon of heating and cooling in horizontal tubes. The study found that \( y^+ \) had a significant impact on the prediction results. While considering the experimental uncertainty, the impact of Prt on the prediction results is negligible. One thing to note is that the effect of buoyancy was ignored. Kim [4] studied the heat transfer characteristics of supercritical fluid in the heated vertical pipe. In the process of considering the buoyancy force, the prediction result of the RNG k-\( \varepsilon \) turbulence model has large differences. In addition, the calculations of the Abid model [5] and the k-w model show a sudden change in wall temperature, especially at larger heat flux, which is different from the experimental results. He [6] found that both V2F and AKN turbulence models can predict the heat transfer deterioration due to buoyancy during the upflow process, but the prediction results of the AKN model are more excellent in the wall temperature distribution. While Sharabi [7] predicted the results of Pis'menny's supercritical heat transfer experiments [8], it was also found that the calculation results of the AKN model were closer to the experimental values.

In a supercritical Brayton cycle, the cooling process of supercritical CO\textsubscript{2} releases heat to the outside, and its performance directly affects system efficiency and compression inlet conditions. The physical properties of supercritical CO\textsubscript{2} will change greatly near the pseudo-critical temperature. Therefore, the heat-transfer characteristics of supercritical CO\textsubscript{2} in the conjugate cooling process are
very different from those of conventional fluids. Therefore, this paper will study the supercritical CO$_2$ heat transfer characteristics in conjugate cooling, and provide important reference for cooler design and improvement.

2. Physical model
Supercritical coolers generally use small-diameter heat exchangers. The heat transfer pipe diameter is generally not more than 2 mm. As shown in figure 1, the diameter of the center pipe is $d_i=2.0$ mm and $d_o=3.0$ mm, the diameter of the shell is 10 mm, and the spacing between the pipe and shell is $S=3.5$ mm. The flow development section is $L/d_i=100$, the cooling section is $L/d_i=200$, and the fluid outlet section is $L/d_i=100$. Supercritical CO$_2$ flows in the tube side, while low-temperature normal-pressure water flows on the outside. Heat is transferred from supercritical CO$_2$ to cooling water through the tube wall. Since the pressure range of supercritical CO$_2$ as a heat transfer medium is generally between 8 and 10 MPa, the operating pressure in the tube side is selected to be 8.8 MPa.

![Figure 1](image)

Figure 1. Physical model of the heat transfer channel (Upflow, reverse g when downflow).

3. Mathematical model
The supercritical CO$_2$ flow in the channel is steady-state and single-phase process. The numerical study of the supercritical fluid adopts the conservation equations. The AKN $k$-$\varepsilon$ model was selected in this paper [9]. The specific equations are as follows:

$$\frac{\partial}{\partial x_i} (\rho u_i) = 0 \quad (1)$$

$$\frac{\partial}{\partial x_j} (\rho u_i u_j) = \frac{\partial}{\partial x_j} \left[ (\mu + \mu_t) \frac{\partial u_i}{\partial x_j} \right] - \frac{\partial p}{\partial x_i} + \rho g_i \quad (2)$$

$$\frac{\partial}{\partial x_i} \left( u_i (\rho E + p) \right) = \frac{\partial}{\partial x_i} \left[ \left( \lambda + \frac{c_p \mu_t}{Pr_t} \right) \frac{\partial T}{\partial x_i} + u_i T_{ij} \right] \quad (3)$$

Figure 2 compares the wall temperatures for supercritical CO$_2$ flowing in the vertical tube. The V2F and AKN models could predict a clearer occurrence of the wall temperature decrease and a closer wall temperature compared with the other models. In addition, the AKN model shows better performance. Therefore, this mathematical model can be used for the numerical simulation of supercritical fluid in the conjugate cooling.
Figure 2. The simulation and experimental results.

4. Results and discussion

Figure 3 shows the heat transfer coefficients in the tube side and the bulk temperature under various thermal wall conditions. The heat transfer coefficient and the fluid temperature distribution of the conjugate cooling process and the constant wall temperature are similar. Because the tube wall temperature is close to the cooling water. The peak value of the local heat transfer coefficient under the constant wall temperature condition will be higher than the conjugate cooling process, and the deviation will further increase under extreme operating conditions. Under the assumption of constant heat flux, the cooling rate of CO$_2$ is relatively slow. Although the heat transfer coefficient also shows a peak, the peak position is backward, and the peak value is only 55% of the Conjugate cooling condition. Therefore, the heat transfer characteristics obtained by constant heat flux and constant wall temperature cannot be directly applied to the Conjugate cooling process.

Figure 3. Heat transfer characteristics with different boundary conditions.

Figure 4 shows the heat transfer coefficients under different cooling water temperatures at Re$_{\text{shell,0}}$=8430, Re$_{\text{CO2}}$=4340 and T$_{\text{CO2}}$=353 K. The heat transfer coefficient of the supercritical fluid will increase first and then decrease. When the fluid temperature exceeds the pseudo-critical temperature, a local peak of heat transfer coefficient occurs. This peak can exceed the normal heat transfer coefficient by more than 4 times. This phenomenon indicates that local heat transfer enhancement occurs during the conjugate cooling. When the supercritical fluid is cooled in the tube, the density of the fluid near the near wall increases drastically, but the density of the main fluid is still small. Due to the effect of buoyancy, a large velocity gradient appears near the wall. In addition, as the temperature of the cooling water increases, the heat transfer coefficient will obviously decrease. As the temperature of the cooling water increases from 13°C to 23°C, the peak value of the heat transfer coefficient will decrease by 25%, and the main fluid temperature corresponding to the peak is shifted to the pseudo-critical temperature.
This phenomenon is caused by a change in local heat flux during conjugate cooling.

![Figure 4](image1.png)  
**Figure 4.** Heat transfer coefficient at different cooling water temperature.

Figure 5 shows the heat flux and wall temperature of the inner wall at different cooling water temperatures. When heat transfer enhancement occurs, the local heat flux also shows a large increase. As the temperature of the cooling water decreases, the peak value of the heat flux increases from 46800 W/m² to 72700 W/m². The wall temperature is almost proportional to cooling water temperature. The increase of the local heat flux further increases the temperature difference between the near wall and the main fluid, and enhancement of buoyancy also enhances heat transfer. As the temperature of the cooling water decreases, the local heat flux and heat transfer coefficient will show a significant increase, and the local wall temperature will also appear local peak. This shows that the enhanced heat transfer results in a decrease in the temperature difference between the supercritical fluid and the wall.

![Figure 5](image2.png)  
**Figure 5.** Wall heat flux and temperature at different cooling water temperature.

Figure 6 shows the velocity and turbulent kinetic energy at different cooling water inlet temperatures. Under the action of gravity, the local flow velocity decreases or reverses near the tube wall. As the temperature of the cooling water increases, the range of the reverse flow gradually expands, but the maximum reverse velocity gradually decreases. This phenomenon is directly related to the heat transfer coefficient trend in figure 4. As the temperature of the cooling water increases, the peak heat transfer coefficient decreases, but the influence range increases. This phenomenon is due to the fact that the rate of supercritical fluid temperature fall slows down, and the temperature of the fluid near the wall increases. The difference in density between the main fluid and the fluid near the wall is reduced, resulting in a relative decrease in the buoyancy. The reverse flow velocity of the high-density fluid near the wall is reduced, the local velocity gradient and the corresponding turbulent energy enhancement phenomenon near the wall is reduced. However, due to the decrease in the cooling rate, the range of the reverse flow region tends to increase.
Figure 6. Variations of velocity (a, b, c) and turbulent kinetic energy (d, e, f).

Figure 7 shows the variation of the heat transfer coefficients in different Re$_{shell,0}$ under $T_{shell,0}=286$ K, $Re_{CO2}=4340$ and $T_{CO2}=353$ K. As the supercritical fluid temperature gradually decreases, the local peak of the heat transfer coefficient occurs before the critical temperature. Due to the influence of the physical properties of the supercritical fluid, the peak of the heat transfer coefficient appears at the position of $L/d_i=15$. The temperature of the fluid in the tube is slightly higher than the quasi-critical temperature. In addition, the lower wall temperature causes a sharp increase in the density of the fluid near the wall, and the buoyancy leads to heat transfer enhancement. When Re$_{shell,0}$ increases from 4215 to 16860, there is a certain difference in heat transfer coefficient before cooling to the critical temperature. The peak value of the heat transfer coefficient increases by 9% with the increase of Re$_{shell,0}$, and the temperature of the main fluid corresponding to the peak is reduced from 320K to 318K. This is because with the increase of Re$_{shell,0}$, the flow rate and the turbulence of the cooling water increase, and the heat transfer between the cooling water and the outer wall of the tube is enhanced. The temperature difference between the wall surface and the supercritical fluid is increased, resulting in the non-uniformity density distribution. Relative to the influence of the cooling water temperature, the change of the cooling water Re has little effect on the heat transfer characteristics of the supercritical fluid in the tube.

Figure 7. Heat transfer coefficient under different cooling water Re.

Figure 8 shows the changes in heat flux and wall temperature for the inner wall of the tube under different Re$_{shell,0}$. When the Re$_{shell,0}$ increases by 4 times, the temperature of the tube wall is significantly lowered, and the maximum wall temperature drops by 4 K. However, the wall heat flux did not change significantly, only a 17% increase in the local heat flux peak. This phenomenon indicates that with the increase of Re$_{shell,0}$, the wall temperature is closer to the cooling water, resulting in an increase in the heat transfer temperature difference in the tube. However, although the cooling water Re increases by
400%, the local heat flux of the inner wall of the tube changes little.

Figure 8. Variations of heat flux and wall temperature under different cooling water Re.

Figure 9 shows the distribution of axial velocity and turbulent kinetic energy at different Re_{shell,0}. The distributions of velocity and turbulent energy are very close under three conditions. Therefore, it can be considered that Re_{shell,0} increased from 4215 to 16860, but the heat transfer process of the supercritical fluid in the tube did not change significantly. This is due to the rise of Re_{shell,0}, which directly leads to an increase in the heat transfer coefficient of cooling water, resulting in a corresponding decrease in wall temperature to balance the heat flux there. It can be considered that the supercritical fluid can be autoadaptation to different shell side states during the conjugate cooling process. When the Re_{shell,0} increases, the heat transfer coefficient of cooling water increases, which causes the temperature of the tube wall to shift to the cooling water temperature. But the heat transfer enhancement phenomenon of the supercritical fluid in the tube also can change the wall temperature. The wall temperature is balanced by both supercritical fluid and the cooling water, which ultimately results in that local heat flux is very close under three conditions.

Figure 9. Variations of the velocity (a, b, c) and turbulent kinetic energy (d, e, f).

5. Conclusions
To understand the supercritical fluids heat transfer in conjugate cooling, the numerical simulation of supercritical CO\textsubscript{2} heat transfer are carried out under gravity. The following conclusions are given from the above investigation.

- The assumptions of constant heat flux and constant wall temperature cannot directly predict the Conjugate cooling process of supercritical fluids.
- The supercritical fluid will have heat transfer enhancement during the conjugate cooling. As the cooling water temperature increases, the peak value of the heat transfer coefficient will
decrease, but the range of enhanced heat transfer will increase.

- Relative to the cooling water temperature, the cooling water Re has little effect on the conjugate cooling process.

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