Research Progress of Heat Transfer in Supercritical CO2 Spiral Tube

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Abstract

Because of its high efficiency and compact structure, supercritical CO2 spiral tube heat transfer is widely used in industrial field, this paper reviews the research progress of heat transfer of supercritical CO2 in spiral tube, By comparing the experimental results of domestic and foreign scholars, the qualitative research conclusions of heat transfer deterioration in spiral tube are summarized. In order to further improve the quantitative study of heat transfer deterioration in spiral tube, the problem of chaotic criteria for the discriminant of buoyancy and flow acceleration is put forward. By comparing the correlation of heat transfer coefficient in straight tube and spiral tube, the accuracy and application range of empirical fitting correlation are judged. And put forward some suggestions in the follow-up correlation research.

Keywords

Spiral Tube; Supercritical CO2; Heat Transfer Deterioration; Flow Acceleration; Buoyancy; Research Progress.

1. Introduction

With the rapid growth of people's demand for energy, the contradiction between energy supply side and demand side has become increasingly prominent. While a large amount of energy is consumed, energy consumption has also caused a lot of damage to the ecological environment, and the environmental problems such as greenhouse effect and ozone layer hole have intensified. Energy shortage and environmental damage have become problems that must be solved. How to effectively improve energy efficiency and achieve sustainable development is a hot issue that researchers all over the world urgently need to solve. CO2 has zero ozone depletion potential and the thermal conductivity of CO2 at 0 °C is proved to be 1.4 times that of R12 under the same conditions,so it is gradually used to replace traditional refrigerants such as chlorofluorocarbons[1]. Meanwhile,Supercritical carbon dioxide (s-CO2) is widely used in the field of fossil refrigeration and supercritical power. Supercritical CO2 cycle system uses CO2 to complete Brayton cycle, which can improve the efficiency by 3% - 5% compared with steam cycle.

There are many studies on the heat transfer in supercritical CO2 pipe. For example, By numerical simulation, scholar BAE[2-4] compared the upward and downward flow heat transfer differences of supercritical CO2 in a vertical circular tube with an inner diameter of 6.32mm, and gave the corresponding heat transfer correlation in different regions. Zhao and Liao [5] studied the heat transfer of supercritical CO2 in a horizontal circular tube when Re > 100000, they found that the effect of buoyancy can not be ignored.Then, Kim [6] introduced the buoyancy criterion number based on the experimental data, the formula is as follows:

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$$Bo^* = \frac{Gr}{Re^{2.625}Pr^{0.4}}\left(\frac{\rho_b}{\rho_w}\right)^{0.5}\left(\frac{\mu_w}{\mu_b}\right) \quad (1)$$

Based on Kim's formula ,Tanimizu [7] proposed using three buoyancy criteria to predict the influence of buoyancy effect in horizontal circular tube on supercritical CO2 heat transfer. He found that there was little correlation between the change of buoyancy criterion number and the heat transfer of supercritical carbon dioxide, and his conclusion was similar to that of Kim and Jackson.

Most of the above studies on convective heat transfer of supercritical CO2 are about straight circular tubes. Compared with the straight pipe, the spiral pipe has higher space utilization and heat exchange efficiency in industry, which is suitable for the chemical industry and refrigeration industry. This paper summarizes the factors leading to the deterioration of heat transfer in spiral tube, summarizes the research trends of relevant scholars, and puts forward suggestions on the shortcomings of current experimental and simulation research, so as to provide reference ideas for the enhancement of heat transfer in supercritical CO2 spiral tube in the future.

2. Physical Properties of Supercritical CO2

CO2 began to exist as a refrigerant in the early 19th century. It is a non-toxic, colorless gas at room temperature, nonflammable and stable at high temperature.Table1 shows the comparison of thermodynamic characteristics between traditional Freon cryogenic refrigerants and CO2. It can be seen from the table1 that the latent heat of vaporization of carbon dioxide is higher than that commonly used in traditional refrigerants R134a and R22. the academia adopts the critical point proposed by duschek et al. [8], that is, 304.1282 ± 0.0150K and 7.3773 ± 0.003Mpa as the critical point of CO2. If the temperature and pressure rise and exceed the critical temperature and pressure, the fluid will become supercritical fluid.

Table 1. Comparison of thermodynamic characteristics between Freon series refrigerants and CO2

Working medium	critical point(°C)	boiling point(°C)	Three phase point(°C)	Latent heat of vaporization(°C)	Variation range of saturated steam pressure (Mpa)	pressure ratio
ethane	32.3	-88.5	-183.2	489.4	0.1153~1.4156	12.28
propane	96.8	-42	-187.6	428	0.0085~0.2432	28.61
butane	151.9	-0.5	-138.4	378.6	0.00065~0.0449	69.08
R22	96.1	-40.8	-157.4	233.7	0.0065~0.2439	37.52
R134a	100.9	-26.5	-103.3	215.9	0.0102~0.3136	30.75
R21	178.3	8.8	-135	239.4	0.00027~0.02825	104.63
R11	197.9	23.7	-111.1	181.3	0.00013~0.0156	120.00
acetone	235	56.2	-94.3	538.4	$7.33*10^{-6}$~0.0029	395.63
methanol	239	64.6	-97.7	1100	$1.07*10^{-6}$~0.0010	934.58
ethanol	241	78.3	-123	837	$9.91*10^{-8}$~0.00034	3430.88
toluene	320	110.6	-95	351	$1.7*10^{-7}$~0.00022	1294.12
CO2	31.1	-78.5	-56.6	322.42	0.52~7.21	13.87

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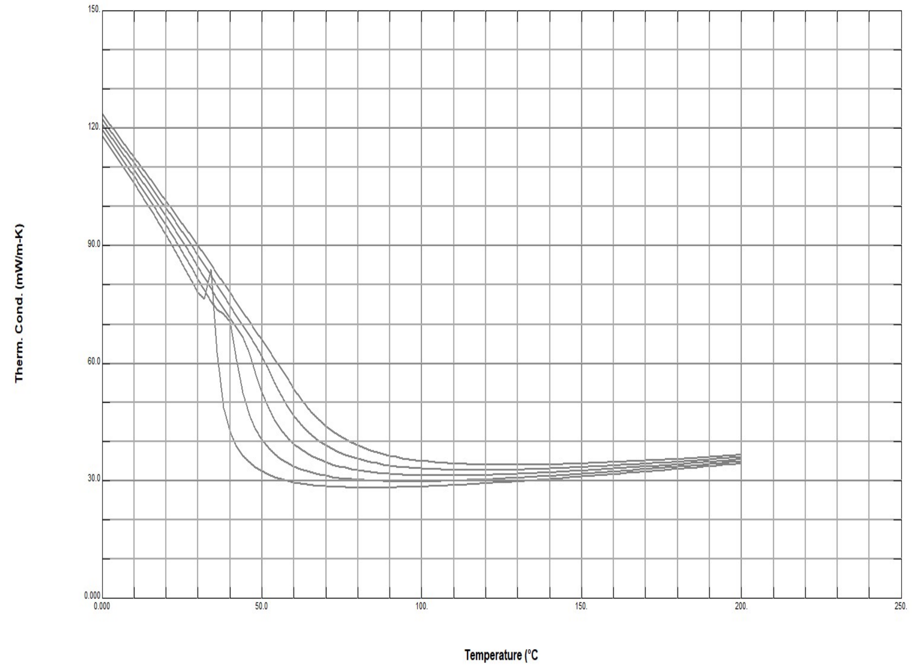
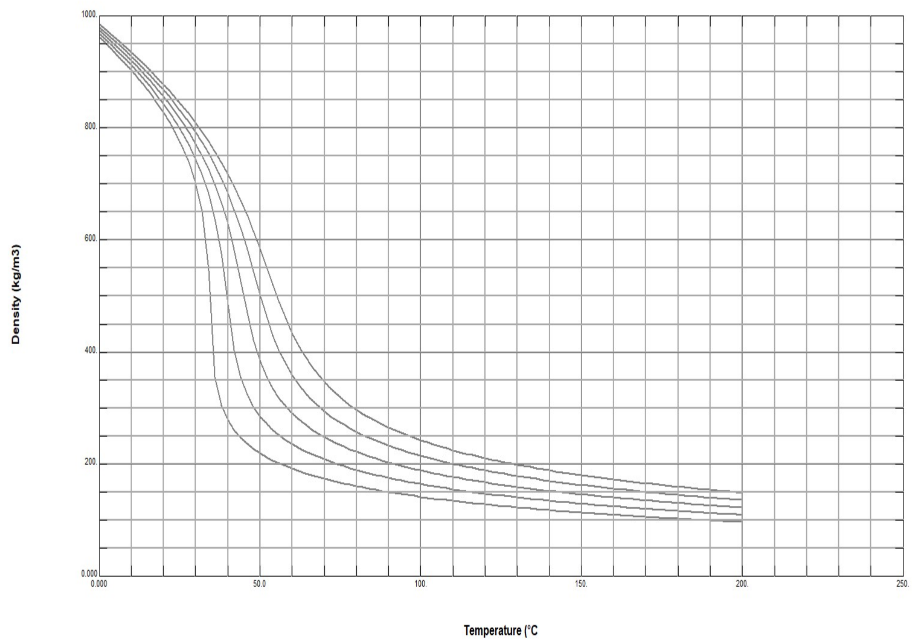
Most of the physical parameters used in the experimental research are based on the data provided by NIST. In this paper, the physical parameters of supercritical pressure CO2 varying with temperature are obtained by using RefProp software. As shown in Figure1, it is the variation diagram of CO2 physical properties with temperature under constant pressure derived from RefProp, The bottom-up pressure of the line segment in the figure is 8Mpa, 9Mpa, 10MPa, 11Mpa and 12MPa.



(a)thermal conductivity



(b)density

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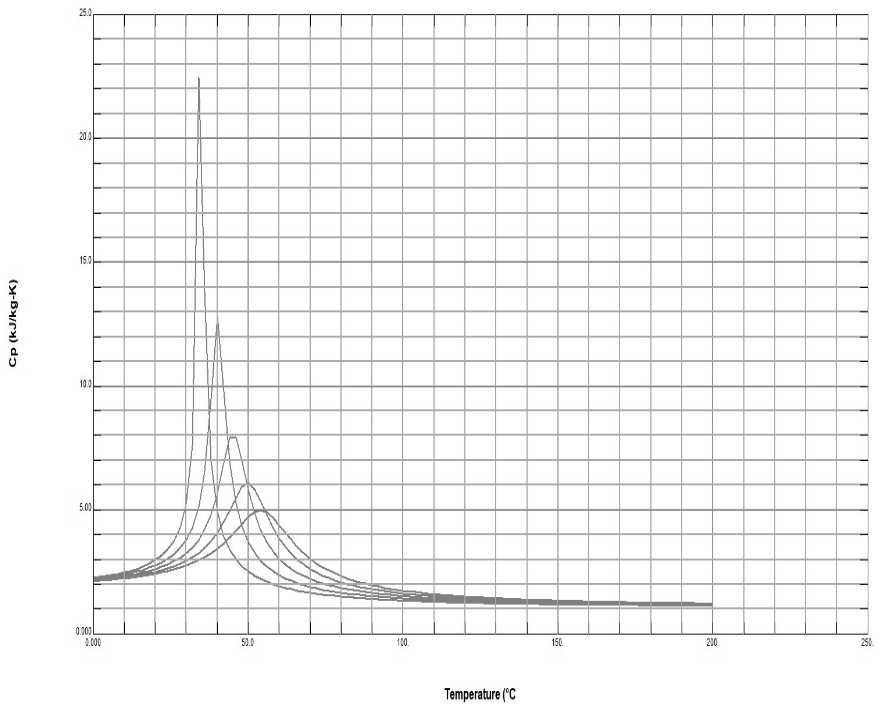
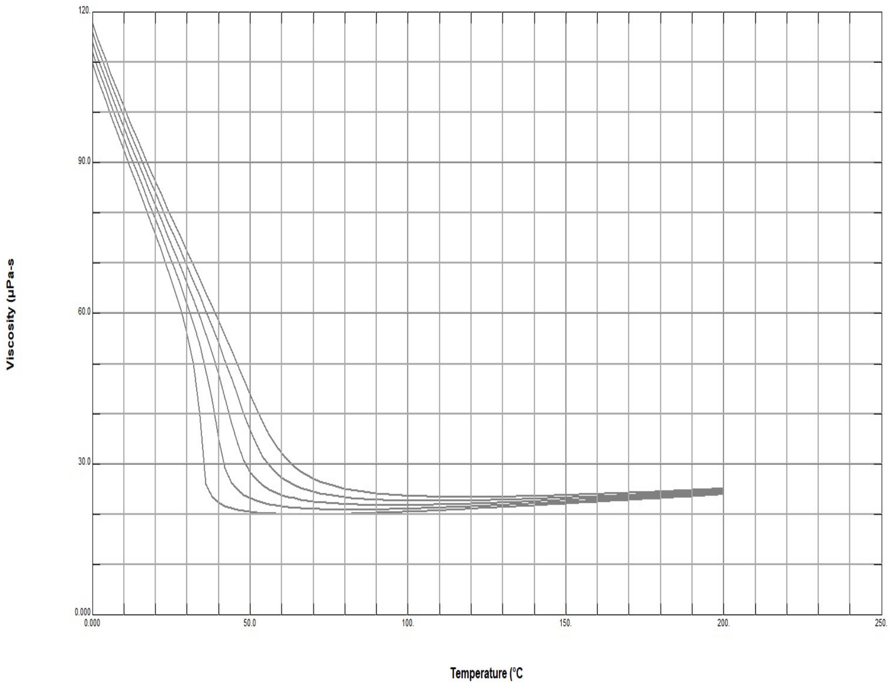


(c)Constant pressure specific heat



(d)Dynamic viscosity

Figure 1. variation of physical properties of S-CO2 with temperature under constant pressure

As shown in Figure 1,with the increase of temperature, the density and dynamic viscosity of fluid decrease monotonically. The specific heat capacity at constant pressure will first increase and then decrease with the increase of temperature, it has a peak value and is located at the quasi critical

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temperature. The thermal conductivity of fluid generally decreases with the increase of temperature, but it fluctuates at the quasi critical temperature and has a local peak. It can be seen that the thermophysical properties of supercritical CO2 change sharply at the critical point, which makes it impossible to bring it into the empirical formula of general constant physical fluids.So the experience of flow and heat transfer for constant physical fluids is no longer applicable to S-CO2.

3. Research Progress on Heat Transfer Deterioration of S-CO2

When dealing with the flow and heat transfer of S-CO2, CO2 fluid should be treated according to variable physical properties. It is precisely because the physical properties of supercritical fluid change greatly with temperature near the critical point, which leads to the change of buoyancy force in the direction of heat flow.

Here we need to introduce another problem, that is, the heat transfer deterioration of supercritical fluid.The deterioration phenomenon is affected by many factors, and the factors leading to deterioration in pipelines with different geometric conditions are also different, which also brings difficulties to the universality of relevant experimental research. The acceptable conclusion in the current research is that mass flow, heat flux, pressure, flow direction, inlet temperature and pipe structure jointly affect the flow and heat transfer of S-CO2. Finally, it can be concluded that the change of buoyancy and flow acceleration caused by the change of density leads to the deterioration of heat transfer.

Adebiyi and hall [9] found that in the horizontal circular tube with an inner diameter of 22.14mm, the cross-section heat transfer coefficient distribution of supercritical CO2 convection heat transfer with constant heat flux is uneven. Finally, they found that the buoyancy force affects the heat transfer at the bus in the tube. Yildiz [10] found that increasing the pipe diameter will lead to local heat transfer deterioration of supercritical fluid, while Rao [11] found that increasing the inlet temperature at the initial stage of heating will lead to the increase of heat transfer coefficient of supercritical fluid. Forooghi [12] compared the effects of pipes with different inclination angles on heat exchange deterioration under the same buoyancy force. He found that as the inclination angle decreased from 90 degrees, there was a gap in the heat transfer coefficient between the upper and lower parts of the pipe, and the deterioration of heat transfer was alleviated.

4. Supercritical CO2 Heat Transfer in Spiral Tube

The structure of spiral pipe is more special than that of straight pipe. Its structure is shown in Figure 2. In the figure, R0 is the tube radius, R is the spiral radius, P is the pitch. Gravity and centrifugal force should be considered when supercritical fluid flows in spiral tube. The complexity of fluid flow in spiral tube also leads to the increase of influencing factors in the process of heat transfer.

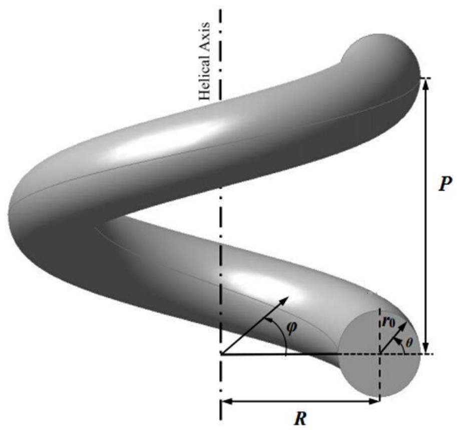

Figure 2. Spiral pipe structure diagram

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The concept of secondary flow is introduced here. Secondary flow refers to the phenomenon that the flow direction deflection is inconsistent with the mainstream direction due to the influence of force or boundary layer in the process of fluid flow. Due to the existence of secondary flow, the re number of the fluid in the spiral pipe is higher than that in the straight pipe. There are many inducements leading to secondary flow, among which centrifugal force is one. In 1959, the scholar Morton [13] experimentally studied the laminar convection in a horizontal pipe uniformly heated at low Reynolds number, and found that the disturbance caused by the buoyancy effect also led to secondary flow. Mao[14] studied the forced convective heat transfer characteristics of water flow in spiral coil. He found that for single-phase steady flow at atmospheric pressure, the influence of secondary flow in spiral coil on convective heat transfer will decrease with the increase of Reynolds number. Mao obtained the heat transfer correlation of supercritical pressure water flowing in spiral coil, as shown in the following (2). The deviation between the predicted results and the experimental results is about 5.26%, which is more accurate.

$$Nu_b = 0.023Re_b^{0.85}Pr_b^{0.4}\left(\frac{\mathrm{d}}{\mathrm{D}}\right)^{0.1}, 3.5\times10^4 \le Re \le 1.2\times10^5$$
$$Nu_b = 0.023Re_b^{0.8}Pr_b^{0.4}\left(1+3.54\frac{d}{D}\right), 1.2\times10^5 \le Re \le 2\times10^5$$
$$Nu_b = 0.023Re_b^{0.8}Pr_b^{0.4}, 2\times10^5 \le Re \le 5\times10^5 \quad (2)$$

Moawed studied the forced convection heat transfer in the spiral tube under the condition of constant heat flow. By comparing the heat transfer in the spiral tube with different spiral diameter and pitch, it was found that the spiral diameter and pitch affected the change of heat transfer coefficient, and put forward the relevant heat transfer correlation:

$$Nu_b = 0.0345Re_b^{0.48}\left(\frac{d}{D}\right)^{0.914}\left(\frac{p}{D}\right)^{0.281}, 600 \le Re \le 2300 \quad (3)$$

The structural parameters of the spiral tube also affect the heat transfer. Liu and masliyah [15] confirmed that the pitch can affect the resistance coefficient of the fluid, and the increase of the pitch within a certain range will lead to the decrease of the resistance coefficient.

4.1 Experimental Research Progress of Heat Transfer in Supercritical CO2 Spiral Tube

In recent years, the research on the heat transfer of supercritical CO2 in spiral tube is limited, and most of its experimental studies are summarized in Table 2.

Wang [16] studied the heat transfer characteristics of vertical spiral tube. The experiment found that the heat transfer characteristics of supercritical CO2 in the tube are jointly affected by the coupling of variable physical properties, buoyancy and centrifugal force. She modified the Dittus Boelter equation by using the density ratio and specific heat capacity ratio, and obtained the correlation formula of the average Nu number. The lower corner marks wi and B respectively indicate that the inner wall temperature and the mainstream temperature of the working medium are qualitative temperatures.

$$Nu = 0.32Re_b^{0.5}Pr_b^{0.4}\left(\frac{\rho_{wi}}{\rho_b}\right)^{0.1}\left(\frac{c_p}{c_{pb}}\right)^{0.4}, T_b < T_{pc}$$

$$Nu = 0.34Re_b^{0.8}Pr_b^{0.6}\left(\frac{\rho_{wi}}{\rho_b}\right)^{0.4}\left(\frac{c_p}{c_{pb}}\right)^{0.8}, T_b > T_{pc} \tag{4}$$

Based on Wang's Nu number correlation, Zhang Wei [17] first proved through experiments that the secondary flow caused by centrifugal force during forced convection and the secondary flow caused by buoyancy force during mixed convection can cause heat transfer enhancement. He analyzed the heat transfer coefficient and found that when the buoyancy parameter $Bo^* \leq 4 \times 10^{-8}$, the effect of buoyancy is negligible; When $4 \times 10^{-8} \leq Bo^* \leq 8 \times 10^{-7}$, the buoyancy begins to inhibit the heat exchange, resulting in the deterioration of the heat exchange; When$Bo^* \geq 8 \times 10^{-7}$, the inhibition effect of heat exchange begins to weaken. Finally, Zhang Wei fitted the empirical correlation of supercritical CO2 heat transfer in the spiral tube through the experimental data, as shown in formula (5):

$$\begin{aligned} Nu &= 0.32Re_b^{0.55}Pr_b^{0.35}\left(\frac{\rho_{wi}}{\rho_b}\right)^{0.1}\left(\frac{c_p}{c_{pb}}\right)^{0.37}, T_b < T_{pc} \\ Nu &= 0.34Re_b^{0.77}Pr_b^{0.57}\left(\frac{\rho_{wi}}{\rho_b}\right)^{0.4}\left(\frac{c_p}{c_{pb}}\right)^{0.84}, T_b > T_{pc} \end{aligned} \tag{5}$$

Table 2. Summary of heat transfer experiments in supercritical CO2 spiral tube

scholar	Spiral tube parameter(mm)	Test conditions
Xu[18]	Inner diameter $d = 9$ Pitch $2\pi b = 32$ Pipe length $L = 5500$ Spiral diameter $2R = 283$	Pressure $8Mpa$ Mass flow $0 \sim 650kg/(m^2.s)$ Heat flux $0 \sim 50kw/m^2$
Wang[16]	Inner diameter $d = 9$ Pitch $2\pi b = 32$ Pipe length $L = 5500$ Spiral diameter $2R = 283$	Pressure $8Mpa$ Mass flow $0 \sim 650kg/(m^2.s)$ Heat flux $0 \sim 50kw/m^2$
Zhang wei [17]	Inner diameter $d = 9$ Pitch $2\pi b = 32$ Pipe length $L = 5500$ Spiral diameter $2R = 283$	Pressure $8Mpa$ Mass flow $0 \sim 650kg/(m^2.s)$ Heat flux $0.4 \sim 50kw/m^2$
Liu[19]	Inner diameter $d = 2 \sim 4$ Pitch $2\pi b = 34 \sim 80$ Pipe length $L = 500$	Pressure $7.5 \sim 9Mpa$ Mass flow $79.6 \sim 283.4kg/(m^2.s$
Xu[20]	Inner diameter $d = 2 \sim 4$ Pitch $2\pi b = 34 \sim 80$ Pipe length $L = 500$	Pressure $7.5 \sim 9Mpa$ Mass flow $79.6 \sim 283.4kg/(m^2.s$
Wang[21]	Inner diameter $d = 4$ Pitch $2\pi b = 34$ Pipe length $L = 560$ Spiral diameter $2R = 72$	Pressure $8 \sim 9Mpa$ Mass flow $159 \sim 318kg/(m^2.s)$ Heat flux $4200 \sim 24300kw/m^2$

4.2 Experimental Research Progress of Heat Transfer in Supercritical CO2 Spiral Tube

Many scholars have also carried out numerical simulation research on the heat transfer characteristics of supercritical fluid in the tube. The cost of numerical simulation is low. At the same time, numerical simulation can not only obtain the basic parameters such as fluid temperature, wall temperature and heat transfer coefficient, but also obtain the dynamic change data of the flow field in the pipe. It is conducive to the quantitative analysis of the operation mechanism of flow heat transfer. Therefore, obtaining the dynamic parameter distribution of supercritical fluid flow region by numerical simulation will make the experimental data more convincing.

Most scholars conduct numerical simulation for the existing turbulence models. Its advantage is that it can save a lot of calculation time and get the flow field information faster. The selection of turbulence model plays a decisive role in the accuracy of numerical simulation, commonly used low Reynolds number turbulence models include LS, MK, AKN, CHC, AB, ys, V2F and SST K- ω Model. HE S [22-23] analyzed the heat transfer characteristics of supercritical CO2 in different turbulence models under the same working condition. Through the comparison of the models, he believed that the inaccuracy of the turbulence model was caused by its inaccurate prediction of the buoyancy term, while the V2F turbulence model was more accurate in the prediction of heat transfer at low Reynolds number. Jiang [24] proposed a calculation model to study the flow and heat transfer characteristics of supercritical water in vertical tubes, through experiments, he found that different heat flux treatment methods will seriously affect the prediction effect of turbulence model on heat transfer deterioration. Other numerical simulations of supercritical CO2 heat transfer in spiral tubes are summarized in Table 3.

Table 3. Summary of numerical simulation of heat transfer in supercritical CO2 spiral tube

scholar	boundary condition	Working condition (mm)	turbulence model	verification
Liu[25]	Constant heat flow	$d = 9$ $2\pi b = 32$ $D = 283$ $L = 5500$	SST k- ω Model	Contrast h Contrast T_w, T_b
Yang[26]	Constant heat flow	$d = 4$ $2\pi b = 10$ $D = 40$ $L = 2000$	RNG k- ε Model	Contrast h
Li[27]	Convective heat transfer	$d = 9$ $2\pi b = 32$ $D = 283$ $L = 5500$	SST k- ω Model	Contrast h Contrast T_w
Zhao[28]	Convective heat transfer	$d = 6$ $D = 80$ $N = 10$	AKN k- ε Model	Contrast h
Zhang[29]	Constant heat flow	$d = 9$ $2\pi b = 32$ $D = 283$ $L = 5500$	SST k- ω Model	Contrast h Contrast T_w, T_b

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By summarizing the supercritical CO2 experiment and numerical simulation in the spiral tube, and comparing the research conclusions of different students, the author finds that the current research on heat transfer in the spiral tube has the following problems:

(1) The author found that most of the Nu number correlations of spiral tubes are modified based on the Nu number correlation of straight tubes because no scholars have specially studied the heat transfer formula in spiral tubes. On the contrary, the study on the heat transfer deterioration of supercritical fluid in straight tube also limits the study of spiral tube heat transfer.

(2) The correlation proposed by many scholars in the experiment does not bring the complex geometric factors of the spiral tube into the formula, and the spiral radius and diameter of the spiral tube have an influence on the heat transfer. At present, the empirical correlation is mostly obtained by fitting the experimental data, which leads to the fact that the correlation must be fitted continuously with the change of working conditions.

(3) Most of the experimental studies on supercritical fluid heat transfer in spiral tubes are smooth circular tubes, but in reality, most of the tubes will wear with service time, and there is no absolutely smooth tube. At present, there are few relevant studies on the impact of the change of pipeline internal roughness on heat transfer, which is still not enough to draw an accurate conclusion.

(4) At present, there is little research on turbulence model in the numerical simulation of supercritical CO2 in spiral tube. Different turbulence models at low Reynolds number will lead to a gap between the simulation results and the experiment, which is between 2% and 11%. How to select the appropriate turbulence model under different working conditions is a research direction of scholars.

5. Conclusion

Through the analysis and induction of literature, many achievements have been made in the research on the heat transfer in supercritical CO2 spiral tube, both qualitative and quantitative. However, scholars' research on heat transfer characteristics in spiral tube still has deficiencies:

(1) Problems in the study of heat transfer deterioration: for the heat transfer deterioration of supercritical CO2 in spiral tube, most of the existing studies are under the condition of low heat flow density, and its empirical formula is not suitable for the condition of high heat flow density; (3) The author analyzed a large number of literatures and found that there is no unified standard for the discrimination of buoyancy in the relevant literature. The criteria for the discrimination of buoyancy and flow acceleration are often the same as scholars. Various scholars have put forward different discriminant, which often leads to great differences in the selection of different discriminant to verify. In the current experimental research, most scholars often use the previous calculation experience, so it is of guiding significance for scholars to specify the criteria under different working conditions.

(2) Problems in numerical simulation research: at present, the simulation research cases of supercritical CO2 in spiral tube are limited, and the influence of different turbulence models used in numerical simulation on the results is not clear, which leads to the lack of persuasion in the relevant research of numerical simulation.

(3) The empirical correlations of supercritical CO2 heat transfer in spiral tube are fitted by the correlations of straight tube, and the accuracy of the formulas is seriously restricted by the working conditions. Including the existing buoyancy formula and flow acceleration formula are lack of standards and systematic evaluation and comparison. Because the discriminant is only demonstrated by the author's personal data, there are few other scholars to verify the correlation. Even after verification, the conclusions obtained under different working conditions are sometimes inaccurate, and it takes time to obtain a large number of data from the verification experiment, which leads to the non universality of most of the newly proposed buoyancy discriminant and flow acceleration discriminant.

For the problems mentioned above, the author puts forward the following suggestions according to the existing experimental conclusions:

(1) The empirical fitting formula is improved. By simplifying the viscosity change into dimensionless number and bringing it into the turbulence formula, the formula of heat transfer coefficient is obtained. On this basis, the calculation formula is continuously improved by increasing dimensionless number.

(2) An experimental device should be established for the flow and heat transfer characteristics of supercritical CO2 in the spiral tube, and the influence of different turbulence models on the numerical simulation results should be verified by analyzing a large number of experimental data under different working conditions. The most suitable working conditions of different turbulence models are summarized, and the criteria for selecting turbulence models under specific working conditions are obtained.

(3) For the evaluation standard of heat transfer deterioration, it is necessary to improve the accuracy of the prediction ability of relevant discriminant formulas, which requires scholars to work together to improve the formula through rigorous data comparison and summarize it into a table as the criterion for later experimental research.

(4) Scholars need to verify the relationship between spiral tube structure and heat transfer deterioration through the combination of experiment and numerical simulation, including the effects of pipe diameter, section geometry, spiral radius and other factors, which still need to be studied by scholars.

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