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Experimental investigation on the pressure drop characteristics of subcritical and supercritical CO_2 heated in a horizontal tube

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A R T I C L E I N F O

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A B S T R A C T

For achieving high-efficiency power generation and refrigeration, CO_2 cycles are receiving great attention and have been widely studied. In these cycles, the in-tube pressure drop of CO_2 determines the required pumping power to maintain tube wall temperature and consequently affects the system efficiency, stability, and safety, and is thus of significant importance. In this work, we experimentally studied the pressure drop characteristics of CO_2 in a horizontal heated tube with an inner diameter of 8 mm under both subcritical and supercritical pressures. The effects of mass flux, heat flux and working pressure on the pressure drop characteristics are investigated and discussed. The pressure drop increases with mass flux and heat flux, but shows complex behavior with varying pressure. The variation of pressure drop with working pressure is attributed to the two-phase effect in both subcritical and supercritical pressures. Moreover, the pressure drop characteristics are compared with existing correlations, and new correlations are developed. For subcritical pressure, a modified Blasius correlation is used to yield a modified Chisholm correlation, which can accurately predict the frictional pressure drop of the experiments. For supercritical pressure, a new correlation is proposed for predicting the friction factors by incorporating the supercritical pseudo-vapor quality, which shows greatly improved prediction accuracy. Our work demonstrates the similarities of the flow characteristics of CO_2 between subcritical and supercritical conditions, and provides an alternative pathway to understand supercritical fluid flow using the three-regime-model by analogy with subcritical two-phase flow.

1. Introduction

Due to the rapid development of supercritical technologies in a variety of industries including materials synthesis, aerospace engineering, advanced power generation, and refrigeration [1–3], significant research interest has been drawn to study supercritical fluids. Among them, supercritical CO_2 (sCO_2) has been widely applied in various systems due to its advantages such as easy availability and safety [4,5]. For examples, the transcritical CO_2 refrigeration cycle has demonstrated successful application in producing and maintaining ice for the speed skating venues during the 2022 Beijing Winter Olympic Games [6], and the sCO_2 Brayton cycle has also shown promising prospect in the utilization of low-grade energy [7,8]. In these applications, the flow characteristics of CO_2 in tubes play a very important role and are related to the stability and safety of the systems. In particular, for the evaporator in transcritical CO_2 cycles and the cooling wall in sCO_2 Brayton cycles, CO_2 flows inside tubes under heating conditions, and the in-tube pressure drop determines the required pumping power to maintain tube wall temperature and consequently affects the system efficiency. Therefore, investigation of the flow resistance characteristics for CO_2 in tubes under heating conditions can provide a basis for the design and operation of these advanced power generation and refrigeration cycles.

For flow resistance characteristics under subcritical conditions, the frictional pressure drop of single-phase flow can be quite accurately predicted by classical empirical correlations. For two-phase flow, it is difficult to develop a unified correlation because of the complexity of the two-phase flow such as various flow patterns, flow instabilities, and large variation of fluid properties. Therefore, many investigations have focused on the prediction of pressure drop in the two-phase regime for various types of fluid. Muller-steinhagen and Heck [9] proposed a correlation for pressure drop

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Nomenclature

Ch	a new dimensionless parameter used in Fang correlation
d	tube diameter, m
e	error
Fr	Froude number
f	friction factor
G	mass flux, kg/m^2s
g	gravitational acceleration, m/s^2
i	enthalpy, kJ/kg
K	supercritical *K* number
L	tube length, m
m	mass flow rate, kg/s
Nu	Nusselt number
P	pressure, Pa
q	wall heat flux, W/m^2
Re	Reynolds number
T	temperature, K or°C
We	Weber number
x	vapor quality
z	axial location, m

Greek symbols

Δi_{pb}	pseudo-boiling enthalpy, J/kg
Δi_{st}	structural contribution in the pseudo-boiling enthalpy, J/kg
Δi_{th}	thermal contribution in the pseudo-boiling enthalpy, J/kg
α	void friction
ε	roughness, m
μ	dynamic viscosity, Pa·s
ρ	density, kg/m^3
σ	surface tension

Subscripts

A	mean relative
ave	average
ac	acceleration
b	bulk fluid
c	critical point
exp	experiment
f	friction
i	inner wall
in	inlet
L	saturated liquid
LO	liquid only
VO	vapor only
out	outlet
pre	prediction
R	mean absolute relative
S	root-mean-square relative
sub	subcritical
sup	supercritical
TP	two-phase
V	saturated vapor
w	inner wall condition
0	saturated liquid at 0 °C

of in-tube two-phase flow based on 9300 data points for various working fluids including water, water-air mixture, water-oil mixture and various refrigerants. Their new correlation has a simple form with an error of about ±30%. Jung and Radermacher [10] proposed a new correlation for two-phase pressure drop based on over 600 data points for R22, R12, R14 and R52a fluids, and the mean deviation error of the new correlation was 8.4%. Mishima and Hibiki [11] proposed a two-phase pressure drop correlation for small tube diameters ranging from 1∼4 mm for air-water mixture. Taking the tube diameter as a variable, they modified the distribution parameter *C* in Chisholm correlation, and the modified Chisholm correlation showed better prediction accuracy. Tran et al. [12] carried out flow boiling experiment for R134a, R12 and R113 in both circular tubes and rectangular tubes. They compared the experimental pressure drop with the values predicted by five pressure drop correlations, and observed large deviation. Based on the Chisholm correlation, they proposed a new correlation by introducing surface tension, which showed good agreement with their experimental data.

Despite extensive study for various other fluids, the pressure drop characteristics for CO_2 two-phase flow are still insufficient, and there are very few applicable correlations. Yoon et al. [13] experimentally studied the pressure drop characteristics of CO_2 in a tube with diameter of 7.53 mm, and found that the pressure drop increases with increasing mass flux and decreases with increasing saturation temperature. They also compared the predicted values of Chisholm and Jung correlation and the experimental values and found an average deviation of 87%. Therefore, based on the Chisholm correlation, they introduced the *We* number to reflect the influence of surface tension on the pressure drop of two-phase flow, and obtained improved prediction accuracy. For CO_2 flowing in a horizontal tube with an inner diameter of 4.57 mm, Oh and Son [14] also observed increasing pressure drop with increasing mass flux and decreasing pressure drop with increasing saturation temperature. They found that most of the existing correlations underestimate the experimental pressure drop. Cho and Kim [15] conducted experiments of CO_2 flowing in smooth and micro-fin tubes with outer diameters of 5 and 9.52 mm, respectively. They found that the heat transfer of CO_2 in micro-fin tubes was significantly better than that in smooth tubes, and there is no significant difference in the pressure drop between the two tubes. It is also found that the correlation proposed by Chisholm for micro-fin tube is not applicable, so it is necessary to establish a two-phase pressure drop correlation suitable for CO_2 flow in micro-fin tube. Park and Hrnjak [16] compared the heat transfer and pressure drop characteristics of CO_2 and R410A refrigerant in a horizontal smooth tube with an inner diameter of 6.1 mm, and found that compared with R410A, the heat transfer performance of CO_2 was significantly improved, and the pressure drop of CO_2 in the tube was smaller.

For supercritical fluids, although they are not as complex compared with subcritical two-phase flow, the variation of thermophysical properties cannot be ignored. Most existing studies for flow resistance characteristics of supercritical fluids propose correlations based on those for single-phase fluid and introduce correction terms to account for the variation of properties. Yamashita et al. [17] studied the pressure drop characteristics of supercritical HCFC22 heated in a vertical tube with an inner diameter of 4.4 mm and found that the frictional pressure drop is smaller when the heat flux is larger in the near-pseudo-critical region. Yoon et al. [18] investigated sCO_2 cooled in a horizontal tube with inner diameter of 7.73 mm, and found that the predicted friction factors values from Blasius correlation are in good agreement with the experimental values with the root mean square error being only 5.9%. Lei et al. [19] investigated the flow resistance characteristics of supercritical water in heated smooth and internally ribbed tubes through experiments and numerical simulations, and found that the predicted values from existing correlations in the literature deviate significantly from the experimental values. Hence, they proposed two correlations for friction factors based on their own experimental data for smooth tube and internal ribbed tube, respectively. Fang et al. [20] conducted a comparative study on the existing friction factors correlations for supercritical fluid, and found that the prediction accuracy of the existing correlations is not satisfactory and the existing experimental results and some correlations are even contradictory. They believed that the main reason for this deviation is that the tube wall roughness was not taken into account in the previous prediction correlations, so they proposed a modified single-phase friction factors correlation by considering the influence of roughness, which resulted in significant improvement in the prediction accuracy. Liu et al. [21] experimentally studied the heat transfer and pressure drop characteristics of sCO_2 cooled in horizontal tubes with inner diameter of 4, 6 and 10.7 mm, and found that the pressure drop increases with increasing mass flux and decreases with increasing inlet pressure, and the experimental values of pressure drop are in good agreement with the values predicted by Blasius correlation. Parahovnik et al. [22] conducted experiments for water and sCO_2 heated in microtubes, and found that heat flux has negligible effect on the pressure drop. Recently, Zhang et al. [23] experimentally investigated the heat transfer and pressure drop characteristics of sCO_2 in heated vertical tubes with inner diameter of 8, 10 and 12 mm. Using the concept of supercritical pseudo-boiling, they found the connection between heat transfer and pressure drop by the dimensionless supercritical K number. They proposed a correlation for friction factor, which incorporates the K number and shows significantly improved prediction accuracy.

The above literature review shows that existing studies for flow resistance characteristics mostly studied the subcritical and supercritical conditions separately, although success has been demonstrated to study the supercritical pressure drop using a supercritical two-phase concept [23]. Meanwhile, for the pressure drop characteristics for CO_2 flowing in a heated tube horizontally, there are limited available studies, especially for supercritical conditions, and correlations with high prediction accuracy are still lacking for both subcritical and supercritical pressures. In this work, we carry out experiments for CO_2 heated in a horizontal circular tube under both subcritical and supercritical conditions. The inner diameter of the test tube is 8 mm, the pressure range is 5.53~20.30 MPa, the mass flux range is 517.2~1285.0 kg/m^{2}s, and the heat flux range is 100.2~402.9 kW/m^2. The variation of frictional pressure drop for both subcritical to supercritical is analyzed. The effects of mass flux, heat flux, and pressure on the variation of pressure drop are discussed. Similarity in the pressure drop characteristics between subcritical and supercritical pressures is observed and attributed to the pseudo-two-phase effect of supercritical fluid based on the previously established three-regime-model [24]. For subcritical pressures, the experimental pressure drop results are compared with existing correlations for pressure drop of subcritical two-phase flow, and a modified Blasius correlation is introduced into the well-known correlations to yield better prediction accuracy. For supercritical pressures, the experimental results are found to deviate significantly from existing correlations, and a new correlation is proposed incorporating the supercritical pseudo-vapor quality defined by Wang et al. [24], showing improved accuracy. Our work provides the first investigation of the pressure drop characteristics for CO_2 covering wide pressure ranges including both subcritical and supercritical pressures, and demonstrates the similarity between subcritical flow boiling and supercritical pseudo-boiling in terms of flow characteristics, which validates the supercritical three-regime-model.

2. Experimental

2.1. Experimental system

The experimental system is mainly composed of the test section, the CO_2 circulation system, the heating system, the cooling system and the measurement system, as shown in Fig. 1. CO_2 with a purity of >99% is fed from the storage tank into the circulation system through the high-pressure pump, and consecutively flows through the preheater, the test section and the cooler, and finally flows into the CO_2 storage tank to complete a cycle. Direct-current electrical power is applied to the test section to generate Joule heating by controlling the electrical voltage of the power supply, the mass flux is controlled by adjusting the operating power of the high-pressure pump, and the pressure of the test section is controlled by changing the opening of the back pressure valve at the outlet of the test section. Detailed experimental system and procedure can be found in Ref. [25].

2.2. Test section

The test tube used in this work is made of 1Cr18Ni9Ti stainless steel, with an inner diameter of 8 mm, a wall thickness of 2 mm and a total length of 3600 mm, as shown in Fig. 2. Copper plates are welded 800 mm away from both ends of the test tube to serve as the electrodes for heating power supply. The total heating length is 2000 mm. Two sheathed thermocouples are arranged 150 mm away from the copper electrodes for bulk fluid temperature measurement at the inlet and outlet. A pressure gauge is arranged 230 mm away from the inlet copper electrode for pressure measurement, and a differential pressure transducer is arranged between inlet and outlet to measure the pressure difference. K-type thermocouple is welded on the temperature measurement positions to measure the outer wall temperatures of the tube. The entire test section is wrapped with 50 mm thick insulation material to reduce heat loss.

2.3. Data reduction

In this experiment, the directly measured parameters include pressure P, mass flux m, and inlet and outlet temperatures $T_{\mathrm{b,in}}$ and $T_{\mathrm{b,out}}$, where, subscripts in and out represents inlet and outlet conditions, respectively.

The mass flux can be calculated by

$$G = \frac{m}{\frac{1}{4}\pi d_{\mathrm{i}}^2} \tag{1}$$

where, d_{i} is the inner tube diameter.

The inner wall heat flux q can be calculated as

$$q = \frac{Q}{\pi d_{\mathrm{i}} L} \tag{2}$$

where, L is the tube length, and Q is the heating power. The bulk fluid enthalpy at any given axial position z can be determined as

$$i_{\mathrm{b}} = i_{\mathrm{b,in}} + \frac{\pi q d_{\mathrm{i}} z}{m} \tag{3}$$

where, $i_{\mathrm{b,in}}$ is the inlet bulk fluid enthalpy evaluated based on the fluid inlet temperature.

In this work, because the test tube is placed horizontally, the gravitational pressure drop can be neglected. Therefore, the total pressure drop along the tube consists of two parts, namely, the frictional pressure drop ΔP_{f} and the accelerational pressure drop ΔP_{ac}

$$\Delta P = \Delta P_f + \Delta P_{ac} \tag{4}$$

For subcritical pressures, the accelerational pressure drop can be calculated by Carey [26]

$$\Delta P_{\mathrm{ac,sub}} = G^2\left[\left(\frac{(1-x)^2}{\rho_{\mathrm{L}}(1-\alpha)} + \frac{x^2}{\rho_{\mathrm{v}}\alpha}\right)_{\mathrm{out}} - \left(\frac{(1-x)^2}{\rho_{\mathrm{L}}(1-\alpha)} + \frac{x^2}{\rho_{\mathrm{v}}\alpha}\right)_{\mathrm{in}}\right] \tag{5}$$

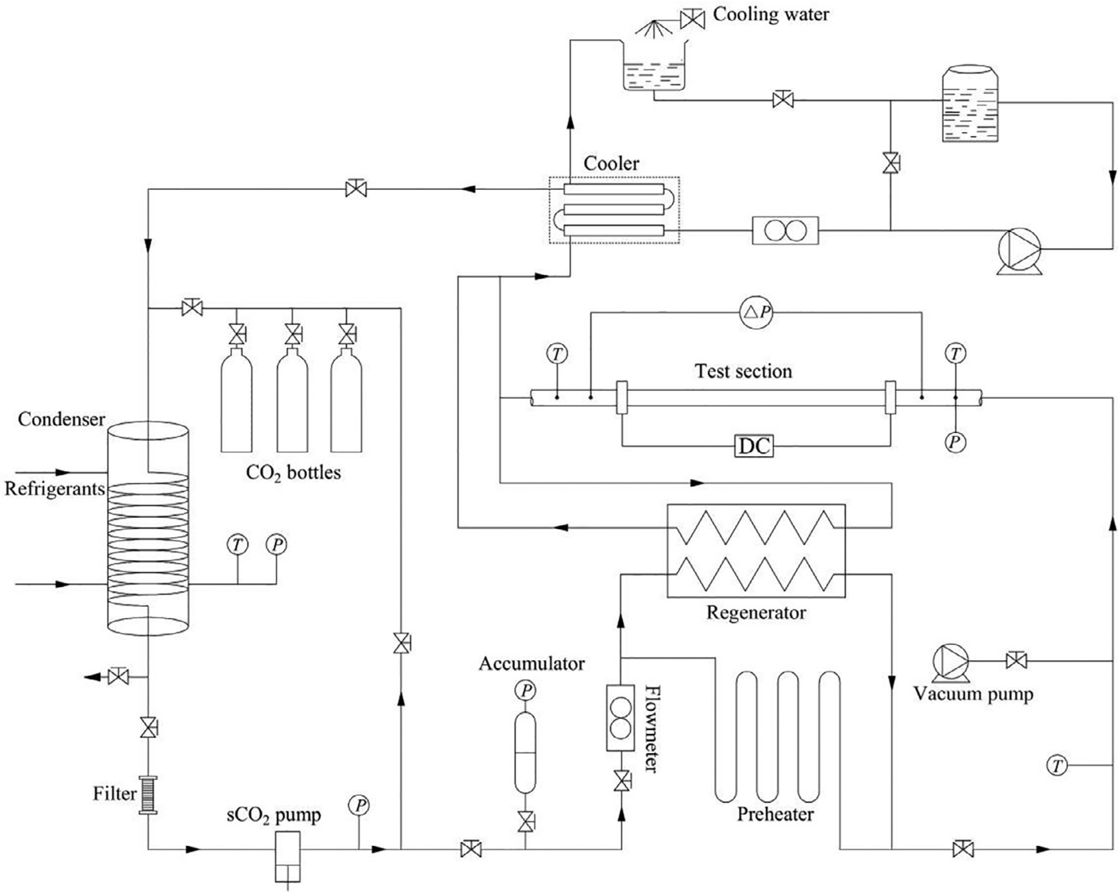

Fig. 1. Schematic of the experimental system.

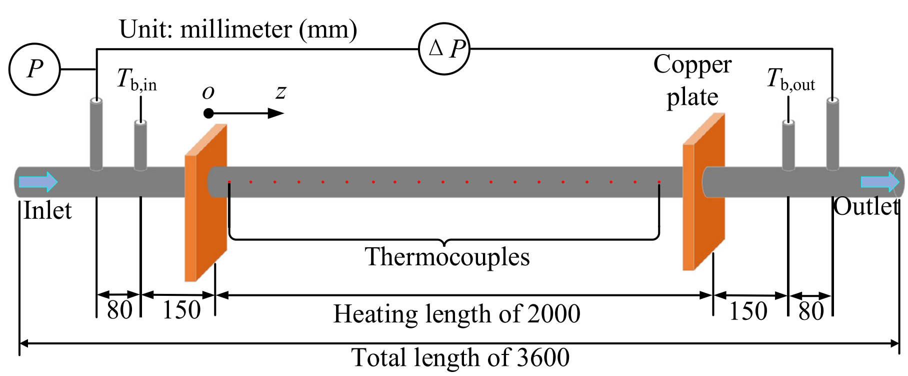

Fig. 2. Schematic of the test tube.

where, x is the vapor quality defined as

$$x = \frac{i_b - i_L}{i_V - i_L} \tag{6}$$

where, i_b is the fluid enthalpy corresponding to the bulk temperature, i_L and i_V are the enthalpies of saturated liquid and saturated vapor, respectively, α is the void fraction represented by

$$\alpha = \frac{x v_V}{(1-x)v_L + x v_V} \tag{7}$$

where, $v_L = {\rho_L}^{-1}$, and $v_V = {\rho_V}^{-1}$, ρ_L and ρ_V are the densities of saturated liquid and vapor, respectively.

For supercritical pressures, the accelerational pressure drop can be expressed as [23]

$$\Delta P_{ac,sub} = G^2\left(\frac{1}{\rho_{out}} - \frac{1}{\rho_{in}}\right) \tag{8}$$

The friction factors for supercritical pressures can be calculated from the following equation.

$$\Delta P_f = \Delta P - \Delta P_{ac} = f\frac{L}{d_i}\frac{G^2}{2\rho_{ave}} \tag{9}$$

where, f is the friction factor, and ρ_{ave} is evaluated using the average temperature along the tube $((T_{in}+T_{out})/2)$ [23].

Table 1 shows the ranges and uncertainties of the experimental parameters. Detailed uncertainty analysis can be found in Ref. [27]

Table 1
Uncertainties and ranges of various parameters.

Value	Range	Maximum Uncertainty
Differential pressure	2.69–43.73 kPa	2.06%
Pressure	5.51–20.41 MPa	0.96%
Bulk-fluid temperature	8.29–231.56 °C	0.5 °C
Mass flux	509.03–1314.22 kg/m^2 s	2.05%
Heat flux	97.98–404.43 kW/m^2 K	5.05%
Friction factor	0.022–0.056	3.0%
Vapor quality	0–1 for subcritical -0.64–4.87 for supercritical	6.11%

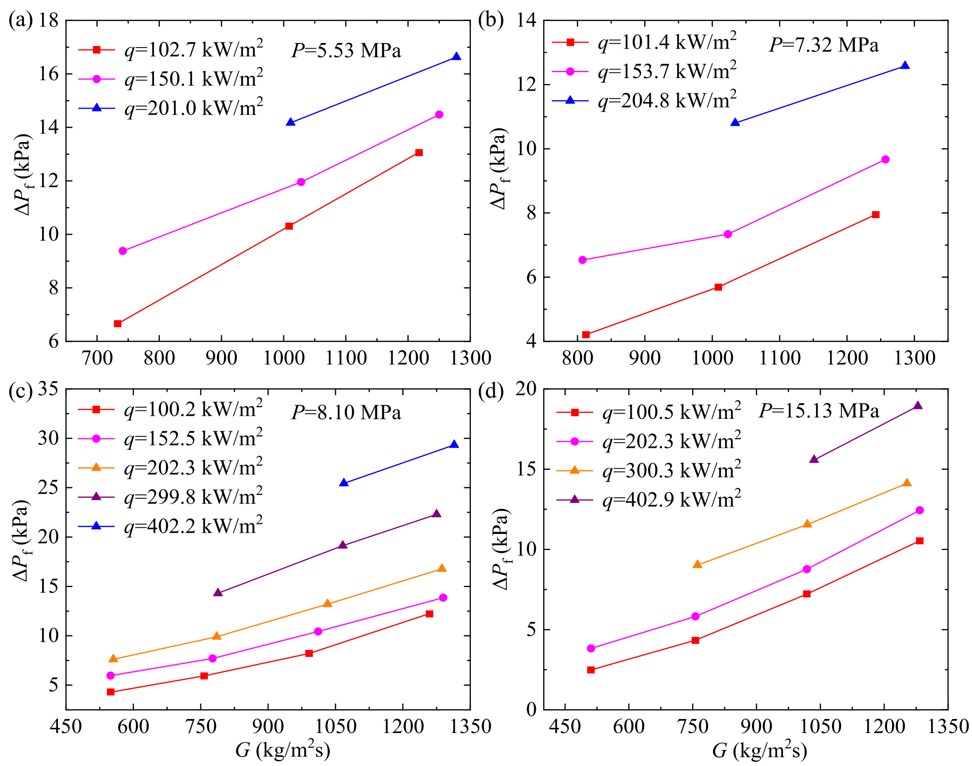

Fig. 3. Variation of frictional pressure drop with mass flux.

3. Results and discussion

3.1. Effects of mass flux and heat flux

Fig. 3 shows the variation of frictional pressure drop with mass flux under different pressures and heat fluxes, with subfigures (a–d) presenting the experimental results under low subcritical pressure, near critical pressure, low supercritical pressure, and high supercritical pressure, respectively. Each subfigure contains several curves for different heat fluxes. It can be seen that the variation trend of frictional pressure drop with mass flux is basically the same under all conditions, where, ΔP_f increases monotonically with G as expected, due to the enhanced turbulence with increasing G. The observed trend is consistent to Tran et al. [12] using R-134a and R-12 as working fluids at subcritical pressures and Zhang et al. [23] in vertical tubes at supercritical pressures.

Fig. 4 shows the variation of frictional pressure drop with heat flux under different pressures and mass fluxes, with subfigures (a–d) presenting the experimental results under low subcritical pressure, near critical pressure, low supercritical pressure, and high supercritical pressure, respectively. Each subfigure contains several curves for different mass fluxes.

The frictional pressure drop increases with increasing heat flux regardless of the pressure condition and the mass flux. This is also similar to the trend reported in Tran et al. [12] for R-134a and R-12 under subcritical conditions and Zhang et al. [23] for CO_2 under supercritical conditions. The former did not give a corresponding explanation, while the latter linked the frictional pressure drop with the deterioration of heat transfer, arguing that the exacerbated heat transfer deterioration caused by increasing heat flux would lead to greater frictional resistance. In this work, the increased frictional pressure drop with increasing heat flux is mainly related to the change of bulk-fluid physical properties. When the pressure, mass flux and inlet temperature are the same, for subcritical conditions, increasing heat flux results in enhanced boiling characteristics and enhanced two-phase interactions. For supercritical conditions, the average bulk-fluid density decreases with increasing heat flux, which causes the average velocity of the cross section to increase, and consequently, the frictional pressure drop increases [21].

3.2. Effect of pressure

Fig. 5 shows the variation of frictional pressure drop with pressure covering both subcritical and supercritical pressures, and the working pressure on the horizontal axis is normalized with the critical pressure. In the subcritical domain, with increasing working pressure, the frictional pressure drop decreases sharply when ap-

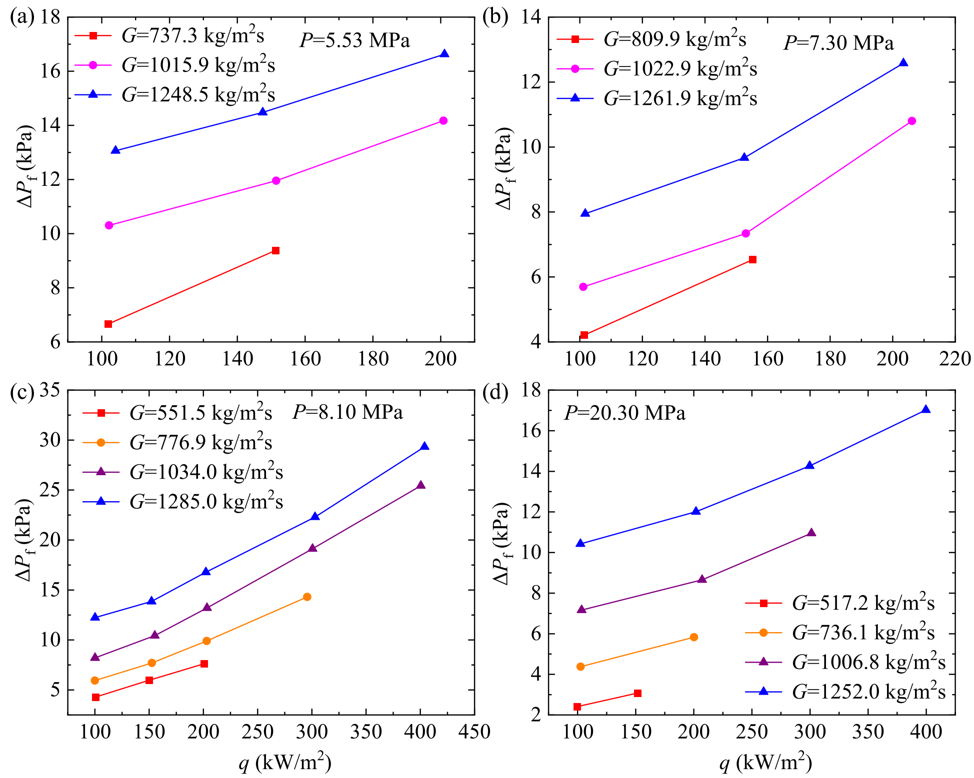

Fig. 4. Variation of frictional pressure drop with heat flux.

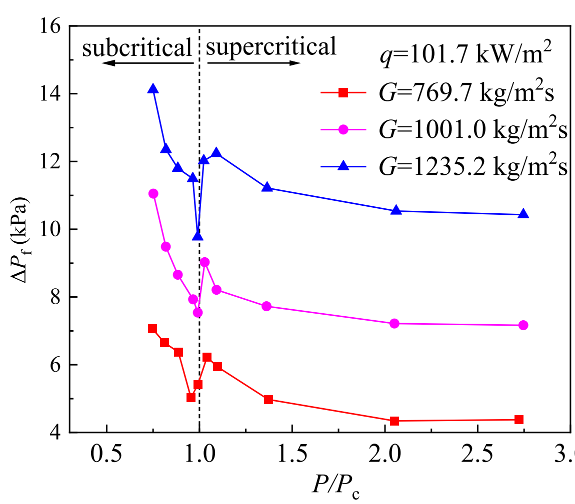

Fig. 5. Variation of frictional pressure drop with P/P_c.

proaching the critical pressure, reaching a minimum value slightly below the critical pressure. Entering the supercritical domain, the frictional pressure drop rises to a higher value after passing the critical point at about 7.57 MPa, and gradually decreases with increasing pressure. It is worth noting that the frictional pressure drop is almost unchanged when the pressure is changed from $2P_c$ to $2.75P_c$. Kondou and Hrnjak [28] also found that the frictional pressure drop of CO_2 decreases with the increase of pressure in the subcritical region, suddenly rises at 7.2 MPa, and then decreases with the pressure again after 7.4 MPa, but they did not give a corresponding explanation. In addition, Song et al. [29] found that the frictional pressure drop of R14 decreases with the increase of pressure under subcritical conditions, which were attributed to the following three reasons: first, increasing pressure leads to increased vapor density and decreased vapor velocity, which reduce the vapor phase frictional pressure drop; second, increasing pressure reduces the liquid viscosity and the friction between liquid and the tube; and third, increasing pressure reduces the liquid density, thus increases the liquid velocity and reduces the slip ratio and the shear force between vapor and liquid phases. Wang et al. [30] found that the pressure drop of supercritical water in the tube also decreases with the increase of pressure. They attributed this phenomenon to the variation of bulk-fluid density under different pressures, that is, higher pressure results in higher bulk-fluid density and lower frictional pressure drop.

Here, we adopt the recently established three-regime-model for supercritical heat transfer to understand the trend observed above from an alternative scope. Under subcritical pressure, increasing the pressure towards the critical pressure results in reduced latent heat and surface tension, and the two phases start to have increasingly similar thermophysical properties. Thus, with pressure increasing towards the critical pressure at subcritical conditions, the complex interactions between liquid and vapor become increasingly negligible, the two-phase effect becomes increasingly small, and the flow and heat transfer characteristics become very similar to single-phase convection which has small pressure drop. Therefore, the pressure drop reaches a minimum value when the working pressure is close to the critical pressure. Under supercritical pressures, the enthalpy change during the pseudo-boiling process Δi_{pb} contains both thermal energy Δi_{th} (corresponding to sensible heat) and structural energy Δi_{st} (similar to subcritical latent heat) [31]. Consequently, similar to subcritical conditions, the frictional pressure drop is expected to be large when the two-phase effect is significant to cause complex flow structure and two-phase interaction, corresponding to large structural energy, and small when the flow is similar to single-phase convective flow, corresponding to small structural energy. Indeed, it is observed that for supercritical pressures, the frictional pressure drop first increases with increasing pressure near the critical pressure and then decreases with in-

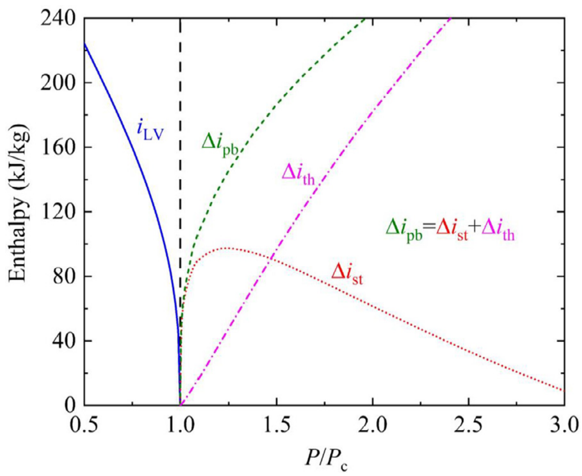

Fig. 6. Variation of latent heat and pseudo-boiling enthalpy with pressure P/P_c. The calculation method of pseudo-boiling enthalpy is obtained from Ref. [31].

creasing pressure at higher pressures, consistent with the trend for the structural energy of pseudo-boiling enthalpy as shown in Fig. 6. Therefore, similar reasons result in the observation of the pressure drop characteristics under subcritical and supercritical pressures, where two-phase effect increases the frictional pressure drop.

3.3. Pressure drop correlation for subcritical two-phase flow

The frictional pressure drop of subcritical two-phase flow is a complicated problem. Most of the correlations in the literature are obtained based on the data of water, R134a, R22, etc., while correlations for CO_2 are rarely reported. The two most commonly used correlations are the Chisholm [32] and Friedel [33] correlations, which are based on water and conventional refrigerants, as follows:

(1) Chisholm correlation

$$\Delta P_{TP} = \Delta P_{LO} \cdot \left\{1 + (X^2 - 1)\left[Bx^{0.875}(1-x)^{0.875} + x^{1.75}\right]\right\} \tag{10}$$

$$X^2 = \frac{\Delta P_{VO}}{\Delta P_{LO}} \tag{11}$$

Here, LO represents the situation when the entire tube is filled with liquid, VO represents the situation when the entire tube is filled with vapor, and ΔP_{LO} and ΔP_{VO} are defined as follows

$$\Delta P_{LO} = \frac{2 f_{LO} L G^2}{d_i \rho_L}, \Delta P_{VO} = \frac{2 f_{VO} L G^2}{d_i \rho_V} \tag{12}$$

where, f_{LO} and f_{VO} are calculated using the Blasius correlation as follows

$$f_{LO} = \frac{0.0791}{Re_{LO}^{0.25}}, f_{VO} = \frac{0.0791}{Re_{VO}^{0.25}} \tag{13}$$

The Re_{LO} and Re_{VO} are calculated by

$$Re_{LO} = \frac{G d_i}{\mu_L}, Re_{VO} = \frac{G d_i}{\mu_V} \tag{14}$$

where, μ_L and μ_V represents the viscosity of saturated liquid and saturated vapor, respectively.

In Eq. (10), the value of B depends on X and the mass flux as follows:

When $0<X<9.5$,

$$B = \begin{cases} 4.8, & G < 500\text{kg/m}^2\text{s} \\ \frac{2400}{G}, & 500 < G < 1900\text{kg/m}^2\text{s} \\ \frac{55}{\sqrt{G}}, & G \geq 1900\text{kg/m}^2\text{s} \end{cases} \tag{15}$$

When $9.5<X<28$,

$$B = \begin{cases} \frac{520}{X\sqrt{G}}, & G \leq 600\text{kg/m}^2\text{s} \\ \frac{21}{X}, & G > 600\text{kg/m}^2\text{s} \end{cases} \tag{16}$$

When $X>28$,

$$B = \frac{15000}{X^2\sqrt{G}} \tag{17}$$

(2) Friedel correlation

$$\Delta P_{TP} = \Delta P_{LO} \cdot \left(E + \frac{3.24HT}{Fr^{0.045} We_L^{0.035}}\right) \tag{18}$$

where, ΔP_{LO} is the same as defined by Eq. (12), and E, Fr, F, We_L, T are defined as follows

$$E = (1-x)^2 + x^2 \frac{\rho_L f_{VO}}{\rho_V f_{LO}} \tag{19}$$

$$Fr = \frac{G^2}{g d_i \rho_{TP}^2}, We_L = \frac{G^2 d_i}{\sigma \rho_L}, H = x^{0.78}(1-x)^{0.224} \tag{20}$$

$$T = \left(\frac{\rho_L}{\rho_V}\right)^{0.91} \left(\frac{\mu_V}{\mu_L}\right)^{0.19} \left(1 - \frac{\mu_V}{\mu_L}\right)^{0.7} \tag{21}$$

Here, f_{LO} and f_{VO} are defined by Eq. (13), σ is the surface tension, ρ_{TP} is the two-phase mixture density defined as

$$\rho_{TP} = \frac{1}{\left(\frac{x}{\rho_V} + \frac{1-x}{\rho_L}\right)} \tag{22}$$

The two correlations mentioned above are used to calculate the pressure drops under the experimental conditions of this work. The comparison between the predicted values and the experimental values is shown in Fig. 7. Fig. 7 also shows the deviation between the experimental results and correlation predictions, represented by e_A, e_R, and e_S, which are the mean relative error, the mean absolute relative error, and the root mean square error, respectively, defined as

$$e_A = \frac{1}{n}\sum_1^n e_i \times 100\% \tag{23}$$

$$e_R = \frac{1}{n}\sum_1^n |e_i| \times 100\% \tag{24}$$

$$e_S = \sqrt{\frac{1}{n}\sum_1^n (e_i)^2} \times 100\% \tag{25}$$

With a general parameter R, the error for each data point is defined by

$$e_i = \frac{R_{pre} - R_{exp}}{R_{exp}} \tag{26}$$

where, R_{pre} and R_{exp} represent predicted and experimental values, respectively.

As shown in Fig. 7, both correlations underpredict the pressure drops for CO_2 under current experimental conditions. The possible reason for this discrepancy is that these correlations are developed for water instead of CO_2, and the experimental conditions are also different. Water has higher viscosity compared with CO_2, which results in larger Re for CO_2 under similar working conditions and

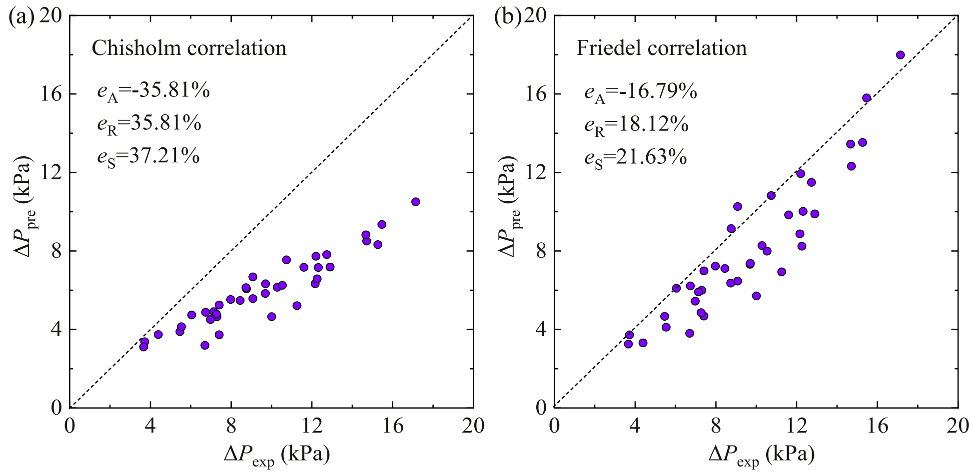

Fig. 7. Comparison between predicted pressure drop using Chisholm and Friedel correlations and the experimental pressure drop for subcritical conditions.

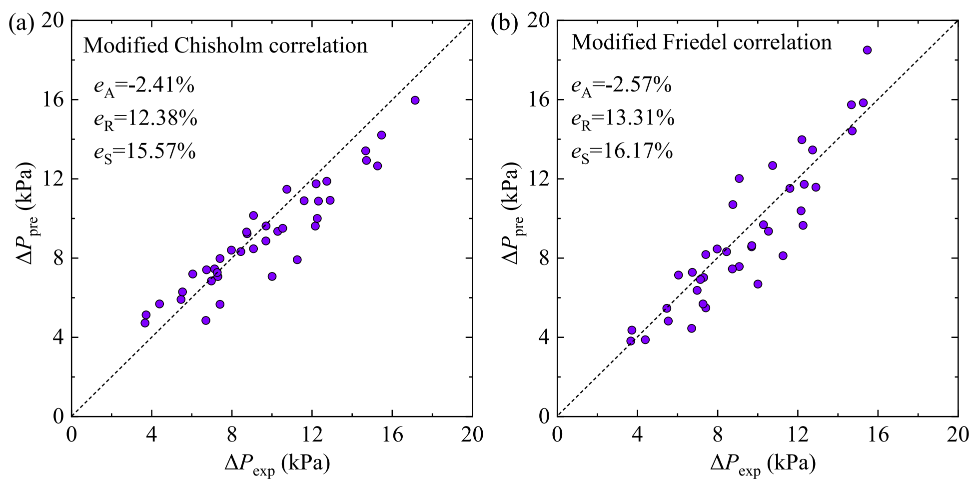

Fig. 8. Comparison between predicted pressure drop using the modified Chisholm and Friedel correlations and the experimental pressure drop for subcritical conditions.

consequently underpredicted pressure drop. Therefore, we propose to use a modified Blasius correlation for CO_2, which is obtained by varying the constant in Eq. (13) to allow the Chisholm and Friedel correlations to fit the experimental results with minimized root mean square error. For Chisholm and Friedel correlations, the obtained constant equals to 0.1201 and 0.0925, respectively, yielding the modified Blasius correlation as

$$f = \frac{0.1201}{Re^{0.25}} \text{ for Chisholm correlation} \tag{27}$$

$$f = \frac{0.0925}{Re^{0.25}} \text{ for Friedel correlation} \tag{28}$$

Subsequently, Eqs. (27) and (28) is used in the Chisholm and Friedel correlations instead of the original Blasius correlation (Eq. (13)) to obtain the modified Chisholm and Friedel correlations.

The comparison between the predicted values using the two modified correlations and the experimental values is shown in Fig. 8. It can be seen that the modified Chisholm and Friedel correlations have greatly improved prediction accuracy. The modified Chisholm correlation has mean relative error, mean absolute relative error, and root mean square error of -2.41%, 12.38% and 15.57%, respectively, and the modified Friedel correlation has mean relative error, mean absolute relative error, and root mean square error of -2.57%, 13.31% and 16.17%, respectively. Therefore, the modified Chisholm correlation is recommended to be used for CO_2 flow boiling under current experimental conditions with the smallest root mean square error.

3.4. Friction factor correlations for supercritical flow

Table 2 lists the existing correlations of friction factors for supercritical flow, and they are used to compare with the experimental results of this work. The Filonenko correlation [34] is a classical correlation for predicting the friction factors for single-phase convective flow. The Petukhov's et al. correlation [35] was proposed for sCO_2 under heating conditions. The Yamashita's et al. correlation [17] is proposed with supercritical R22 as working fluid at low heat flux. The Wang's et al. correlation [30] incorporates the *Pr* number, which is applicable for supercritical water under heating conditions. The Fang's et al. correlation [36] integrates the experimental data of CO_2, water, R22 and other working fluids, and introduces the dimensionless number *Ch* to reflect the influence of pressure, mass flow and enthalpy. The Zhang's et al. correlation [23] is based on the supercritical pseudo-boiling theory and introduces the dimensionless number *K*, which is applicable for sCO_2 under vertical heating conditions.

Fig. 9 shows the comparison between correlation predicted friction factor values and the experimental values. It can be seen from the Fig. 9 that except for the Fang correlation which generally overestimates the friction factors values, the other five correlations all underpredict the friction factors values. All the correlations pro-

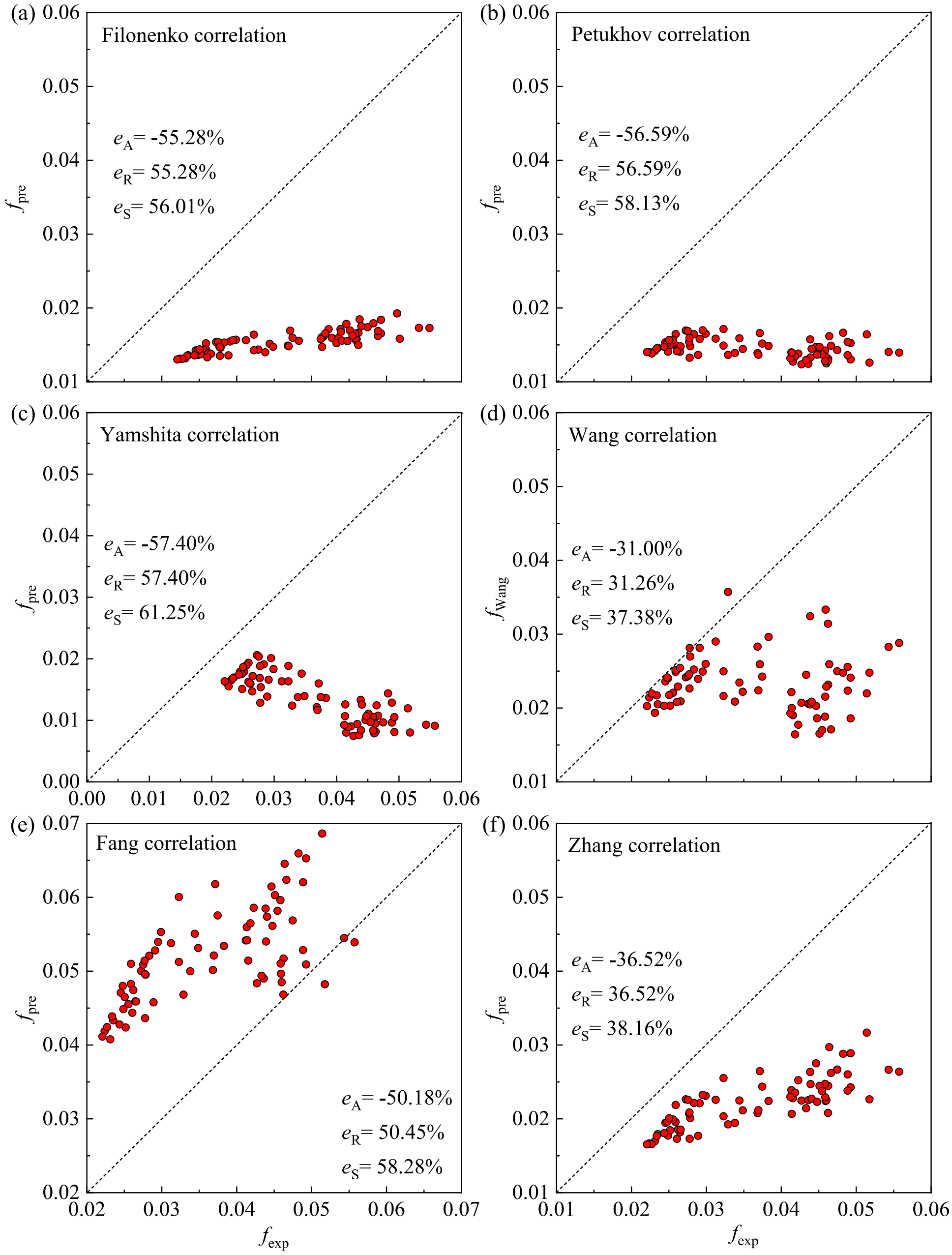

Fig. 9. Comparison between predicted friction factors using various correlations and experimentally obtained friction factors for supercritical conditions.

duce large prediction errors, because they were either developed for other working fluids, or for vertical flow conditions.

From the above analysis, it can be concluded that the existing prediction correlations of friction factors are not suitable for the current experimental conditions for sCO_2 in a horizontal tube. Therefore, we develop a new friction factors correlation based on the experimental results. Fig. 10 shows the variation of experimental friction factors with the average *Re* along the tube, showing the negative correlation as expected. Considering the previous observations that the pressure drop varies with pressure similarly as the latent energy, we expect that the friction factors is affected by the supercritical two-phase effect. Therefore, we adopt the concept of pseudo-vapor quality *x* defined in the three-regime-model [24], and use this parameter to characterize the two-phase effect in supercritical flow. The average temperature in the tube $T_{ave}=(T_{in}+T_{out})/2$ is used as the reference temperature to evaluate the average bulk fluid enthalpy, which is used to calculate the average x_{ave} for each working condition. The variation of friction factors with x_{ave} is shown in Fig. 11. It can be seen that f_{exp} is large when $0<x_{ave}<1$ corresponding to the two-phase-like regime with strong two-phase effect, and is small when $x_{ave}>1$ corresponding to vapor-like regime with negligible two-phase effect, which is consistent with the physical meaning of pseudo-vapor quality and agrees with the previous hypothesis. For the current experimental conditions, the average pseudo-vapor quality is always larger than 0, resulting in the negative correlation between x_{ave} and f_{exp}. Therefore, we incorporate x_{ave} into the friction factor correlation. The new correlation has a form of $f = CRe_{ave}^{n_1}x_{ave}^{n_2}$ with *C*, n_1, and n_2 being constants determined by the principle of least square method [37]. The new correlation for friction factors is finally obtained as

$$f = 1.1228Re_{ave}^{-0.287}x_{ave}^{-0.1078} \tag{29}$$

Table 2
Friction factors correlations for supercritical fluid.

References	Correlations	Working fluids and parameter ranges
Filonenko [34]	$f=(1.82\log 10Re-1.64)^{-2}$	$10^4 \le Re \le 5\times10^6$
Petukhov et al. [35]	$f=(1.82\log 10Re-1.64)^{-2}\left(\frac{\mu_w}{\mu_b}\right)^{0.24}$	CO_2/ P:7.7, 8.9 MPa q: 384–1053 kW/m^2 G:1000–4100 kg/m^{2}s d_{in}=8 mm
Yamashita et al. [17]	$f=\frac{0.314}{0.7-1.65\log Re_b+(\log Re_b)^2}\left(\frac{\mu_w}{\mu_b}\right)^{0.72}$	R22/P=5.5 MPa G=700 kg/m^{2}s q:0–60 kW/m^2 d_{in}=4.4 mm
Wang et al. [30]	$f=(1.82\log 10Re-1.64)^{-2}Pr_b^{0.26}\left(\frac{\mu_b}{\mu_w}\right)^{-0.56}\left(\frac{\rho_b}{\rho_w}\right)^{0.35}$	Water/P:23–28 MPa G:700–1500 kg/m^{2}s q:200–600 kW/m^2
Fang et al. [36]	$f=0.0127[ln(650(\frac{\varepsilon}{d_i})^{0.67}+(\frac{99000}{Re})^{1.32}+0.066Ch)]Ch=\frac{P}{G\sqrt{i-i_0}}$	CO_2, R22, R404A, R134a, R410A, RP-3 and Water
Zhang et al. [23]	$f=2.15Re^{-0.342}K^{0.027}$	CO_2/ P: 7.3–23 MPa G: 500–1500 kg/m^{2}s q: 15–400 kW/m^2 d_{in}=8, 10 and 12 mm

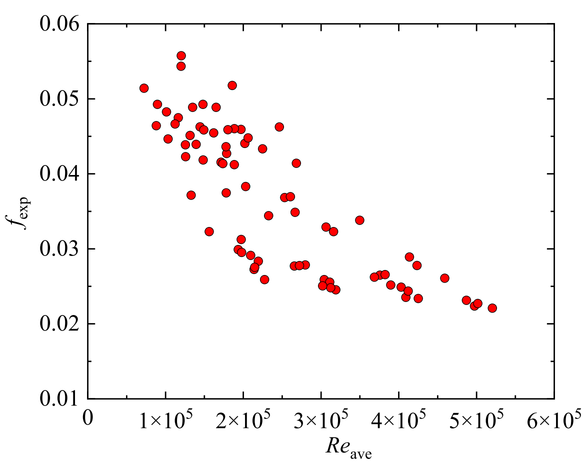

Fig. 10. Variation of f_{exp} with Re_{ave} for supercritical conditions.

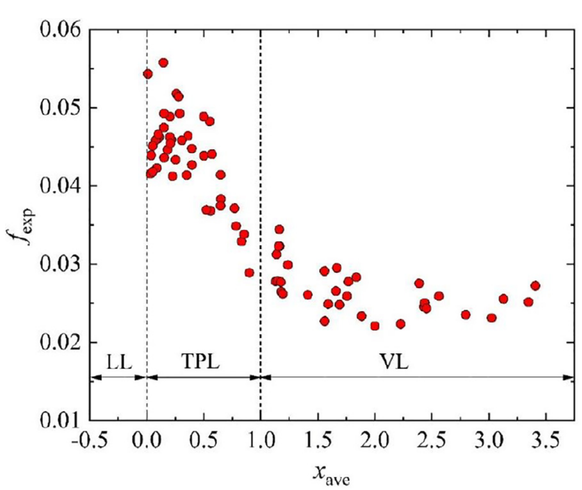

Fig. 11. Variation of f_{exp} with x_{ave} for supercritical conditions. The two-phase-like (TPL) regime shows large friction factor. LL represents liquid-like regime and VL represents vapor-like regime.

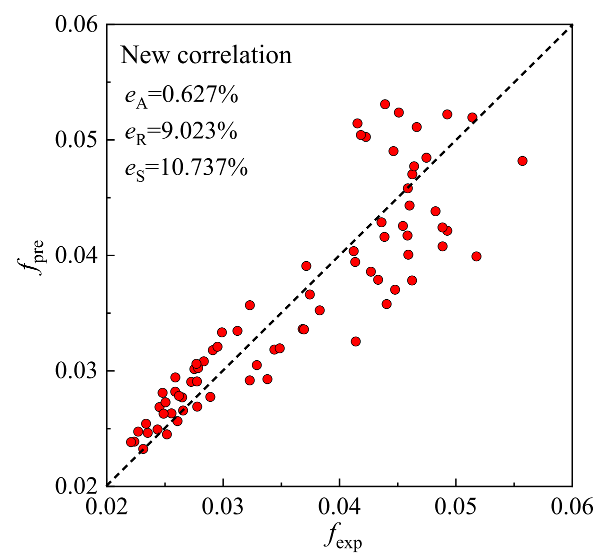

Fig. 12. Comparison between the predicted friction factors using the new correlation and the experimental values for supercritical conditions.

Fig. 12 shows the comparison between the new correlation and the experimental results. The errors e_A, e_R and e_S are 0.627%, 9.023% and 10.737%, respectively, which shows significantly improved prediction accuracy.

4. Conclusions

In this work, the pressure drop characteristics of CO_2 in a horizontal heated tube are experimentally studied. The pressure range covers both subcritical pressure and supercritical pressure. The effects of mass flux, heat flux and working pressure on the pressure drop characteristics are investigated and discussed. For subcritical pressure, a modified Blasius correlation is used to yield a modified Chisholm correlation, which can accurately predict the frictional pressure drop of the experiments. For supercritical pressure, a new correlation is proposed for predicting the friction factors of sCO_2 flowing in the horizontal tube, which shows much improved prediction accuracy. Both correlations are expected to be applicable with different tube diameter conditions, and are suggested to be used to correlate the pressure drop of CO_2 in horizontal tubes under similar parameter ranges in the future. The main conclusions are as follows.

(1) For CO_2 heated in a horizontal tube with inner diameter of 8 mm, the frictional pressure drop increases with increasing mass flux, and increases with increasing heat flux due to changes in physical properties. More interestingly, under subcritical pressures, the pressure drop decreases with increasing fluid pressure, reaching a minimum near the critical pressure. Under supercritical pressures, the pressure drop attains a large value when the pressure slightly exceeds the critical pressure, and then decreases with increasing pressure. The observed trends can be attributed to the two-phase effect in both subcritical and supercritical pressures: when the two-phase effect is more significant, the pressure drop is larger.
(2) For subcritical pressures, the experimental pressure drop values do not agree well with the predicted values by two commonly used correlations. A modified Blasius correlation is used to modify the Chisholm correlation, which yields significantly improved accuracy with mean relative error, mean absolute relative error and root mean square error being -2.41%, 12.38% and 15.57%, respectively.
(3) For supercritical conditions, the experimentally obtained friction factors values are compared to six existing correlations reported in the literature. It is found that all these correlations fail to accurately predict the experimental results, and they are not suitable for sCO_2 in horizontal tubes. A new correlation is proposed considering the two-phase effect in supercritical fluid flow. The new correlation contains the average Re and the average pseudo-vapor quality along the test tube, which shows superior accuracy with the mean relative error, mean absolute relative error and root mean square error being 0.627%, 9.023% and 10.737%, respectively.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Bingtao Hao: Investigation, Validation, Formal analysis, Writing – original draft. **Chengrui Zhang:** Investigation, Validation. **Liangyuan Cheng:** Investigation, Methodology. **Jinliang Xu:** Conceptualization, Supervision, Funding acquisition, Project administration. **Qingyang Wang:** Conceptualization, Supervision, Funding acquisition, Writing – original draft, Writing – review & editing.

Data availability

Data will be made available on request.

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