Experimental Study on the Minimum Drag Coefficient of Supercritical Pressure Water in Horizontal Tubes

Xianliang Lei ^{*a}, Huixiong Li ^a, YuMeng Guo ^a, Qing Zhang ^a, Weiqiang Zhang ^a, Qian Zhang ^a

^a State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University

No.28 West Xian-Ning Road, Xi'an 710049, China

*xianlianglei@mail.xjtu.edu.cn Tel: +86-29-82665870 Fax: +86-29-82669033

Abstract

Hydraulic resistance and its components are of great importance for understanding the turbulence nature of supercritical fluid and establishing prediction methods. Under supercritical pressures, the hydraulic resistance of the fluid exhibits a “pit” in the regions near its pseudo-critical point, which is hereafter called the minimum drag coefficient phenomenon. However, this special phenomenon was paid a little attention before. Hence systematical experiments have been carried out to investigate the hydraulic resistance of supercritical pressure water in both adiabatic and heated horizontal tubes. Parametric effects of heat flux, pressure and mass fluxes to drag coefficient are further compared. It is found that almost all of the existing correlations don't agree well with the experimental data due to the insufficient consideration of thermal-properties near the pseudocritical point. Two correlations of the drag coefficients are finally proposed by introducing the new variable of the derivative of density with respect to temperature or Prandtl number, which can better predict the drag coefficient of isothermal and nonisothermal flow respectively.

Key words: pressure drop, drag coefficient, thermo-hydraulic characteristics, pseudocritical region, supercritical water

1. Introduction

Hydraulic resistance characteristic of supercritical pressure fluids is one of the important issues related with the performance and safety of thermal-hydraulic systems, such as water-walls in the (ultra-) supercritical boiler, steam generator in the Supercritical Water-Cooled Reactors (SCWRs). Recently, due to the increasing requirement of large capacities and high efficiency of supercritical unit, more accurate description of hydraulic resistance has been re-emphasized. This is very significant for understanding the nature in turbulent heat transfer characteristics of supercritical pressure fluids, especially for the cases with strong buoyancy and thermal acceleration effect lead by the steep variation of the thermal properties at supercritical pressures.

In general, the total pressure drop (ΔP_{tot}) can be divided into four parts, including a gravitational pressure drop (ΔP_g), an accelerating pressure drop (ΔP_{ac}), a local pressure drop (ΔP_l) and a frictional pressure drop (ΔP_{fri}), as expressed in Eq.(1). In our experiment, total pressure drop is measured by the differential pressure sensors at the mixing chambers whose locations are the inlet and outlet of the test section.

$$\Delta P_{tot} = \Delta P_{fri} + \Delta P_g + \Delta P_{ac} + \Delta P_l \quad (1)$$

According to the state of fluid at the inlet/outlet of the test section and the configuration of flow path, the corresponding gravitational pressure drop, the accelerating pressure drop (also called inertial resistance), and the local pressure drop can be respectively obtained with Eq.(2)-(4).

$$\Delta P_g = \int_{z_{in}}^{z_{out}} \rho(z) g dz \quad (2)$$

$$\Delta P_{ac} = \rho_{out} u_{out}^2 - \rho_{in} u_{in}^2 = (\overline{\rho u})^2 (S_{b2} / \rho_{out} - S_{b1} / \rho_{in}) \quad (3)$$

$$\Delta P_l = (\xi \frac{\rho u^2 L}{2D}) = (\xi \frac{G^2 L}{2\rho D}) \quad (4)$$

Where, G is mass flux, ρ is density, u is velocity, S is the momentum coefficient (Boussinesq coefficient), ξ is the drag coefficient and the subscript of “in” and “out” respectively indicate the location of test section at the channel inlet and outlet.

It is necessary to have rather detailed information on the averaged flow structure and temperature fields in different cross section of a tube. Due to the difficulties of measurement of supercritical water, such detailed information is absent. Thus a uniform temperature distribution and an invariable momentum coefficient value (for turbulent flow, $S_b=1.02-1.03 \cong 1$) in each cross sections is assumed. The solving method for drag coefficient of supercritical fluids is actually a simplified one-dimensional (homogeneous) flowing model (Kurganov et al., 2013). Combined with Equations (1) ~ (4), the corresponding frictional pressure drop could be obtained by subtracting each calculated components of the pressure drop from the measured total pressure drop. The drag coefficient can be got from Eq. (5),

$$\Delta P_{fri} = (\xi \frac{L}{D} \frac{\rho u^2}{2}) = (\xi \frac{L}{D} \frac{G^2}{2\rho}) \quad (5)$$

For supercritical fluids, the boundary between liquid phase and gas phase disappears and the flow pattern is somewhat similar to the conventional single-phase flow (Cheng and Schulenberg, 2001). Hence it can be assumed that most of the existing classic drag coefficient correlations based on the characteristic of single-phase flow may be still suitable for the flow of supercritical fluids. However, it should be noteworthy that the feature of supercritical fluid is very special. Near the pseudocritical point, the thermal-physical properties present a steep and fast variation (as seen in

Figure 1). The corresponding friction resistance coefficient in the circular channel may be changed, and the previous widely used hydraulic resistance correlations may be no longer sufficient for predicting drag coefficient of supercritical fluids.

Figure 1 Variations of thermophysical properties ((a) density and its gradient, (b) viscosity, (c) thermal-conductivity, (d) specific heat) of water with temperatures under different pressures ($P=23, 25, 27$ and 29 MPa)

A few investigations on the mean hydraulic resistance of supercritical fluid in the heating zone of circular tubes (mainly on water and carbon dioxide) had been reported. Most of previous literatures (Fang et al., 2012; Jackson, 2013; Jiang et al., 2006; Kurganov et al., 2013; Mikheev, 1956; Petrov and Popov, 1985; Yoon et al., 2003), Pioro et al. (Pioro et al., 2004) reviewed the studies on experimental hydraulic resistance of fluids flowing in channels at supercritical pressures. Recently Kurganov (Kurganov et al., 2013) summarized the latest results on the hydraulic pressure and friction resistance in the round tube with both adiabatic and heating states

as well. Angelucci et al. (Angelucci et al., 2013) reproduced the variation of friction factor observed in experimental data by using STAR-CCM+, but their reproduced result is only agree with available correlations in a qualitative way . From the existing literatures, it is clearly known that the special variation of drag coefficient was not given much attention. For example, the special drag coefficient distribution of supercritical water can be observed from the paper of Kondrat'ev et. al (Kondrat'ev, 1969), as shown in Figure 2. However, in order to gain a better drag coefficient correlation, these “bad” points near the pseudocritical region had been ignored by authors, and the reasons for this “pit” phenomenon were ascribed to the effect of fluid acceleration. From Figure 2 it is known that the points lower than 0.16 had been abandoned in the proposing correlation ($\xi \times \text{Re}^{0.22} = 0.188$) of frictional resistance coefficient. Obviously, neglecting the variation of friction factors within the range of pseudocritical region is unreasonable, which would lead to a large deviation between measured and calculated points. The relative error between the minimum ($=0.11$) and the averaged value of $\xi \times \text{Re}^{0.22}$ ($=0.188$) is up to 40% at the pressure of 23.3 MPa.

Figure 2 Variation of hydraulic frictional resistance with bulk fluid temperature in the horizontal polished tube with diameter of 10.47 mm at the pressure of 23.3, 25.3 and 30.4 MPa (data from Kondrat'ev (Kondrat'ev, 1969))

Besides, pressure drop due to flow acceleration, as a major part of whole pressure drop, also has been discussed in the thermal-hydraulic studies. Razumovskiy et al. (Razumovskiy et al., 2008) found that the accelerating pressure drop is a very significant part in the total pressure for vertical channels. Neglecting it may lead to the exaggeration of the frictional pressure drop or friction factor, especially in cases with high ratio of q/G . Tarasova and Leont'ev (Tarasova and Leontev, 1968) also observed an apparent variation occurring within the range of pseudocritical region, but they did not explain it with the thermal acceleration effect. Therefore, based on its complex effect of thermal acceleration to friction resistance coefficient close to the pseudocritical point, further analysis should be conducted.

Until now, several practical prediction correlations for predicting hydraulic resistance in circular tubes have been proposed based on the experimental data and theoretical analysis. For isothermal

flow, the Filonenko equation (Eq.(6)) and Itaya correlation (Itaya, 1945)(Eq.(7)) are widely accepted formulas, where the Itaya and Filonenko correlation is of the form as follows,

$$\xi = (0.79 \ln Re - 1.64)^{-2} \quad (6)$$

$$\xi_{iso} = \frac{0.314}{0.7 - 1.65 \log Re_b + (\log Re_b)^2} \quad (7)$$

For nonisothermal flow of water and other fluids, the drag coefficient can be calculated with the following equations in Table 1.

Table 1. The drag coefficient correlations for nonisothermal flow

No	Author	Equation	Experimental conditions
(8)	Mikheev (Mikheev, 1956)	$\xi = \frac{1}{(1.82 \log_{10} Re_b - 1.64)^2} \left(\frac{Pr_w}{Pr_b} \right)^{1/3}$	Water, $Re > 4000$
(9)	Popov (Popov, 1967)	$\frac{\xi}{\xi_{iso}} = \left(\frac{\rho_w}{\rho_b} \right)^{0.74}$	Carbon dioxide
(10)	Tarasova and Leont'ev (Tarasova and Leontev, 1968)	$\frac{\xi}{\xi_{iso}} = \left(\frac{\mu_w}{\mu_b} \right)^{0.22}$	Water, $d=8.03$ mm, $P=22.6-26.5$ MPa, $G=2000-5000$ kg·m ⁻² ·s ⁻¹ , upward and downward, $q_w=580-2320$ kW·m ⁻²
(11)	Razumovskiy (Razumovskiy et al., 2008)	$\frac{\xi}{\xi_{iso}} = \left(\frac{\rho_w}{\rho_b} \frac{\mu_w}{\mu_b} \right)^{0.15}$	Water, $d=3$ mm, $P=24.5$ MPa $G=500, 1000, 1500$ kg·m ⁻² ·s ⁻¹ , $q/G=0.5-1.5$ kJ·kg ⁻¹
(12)	Kirillov et al. (Kirillov, 2000)	$\frac{\xi}{\xi_{iso}} = \left(\frac{\rho_w}{\rho_b} \right)^{0.4}$	Water, $P=24.5-27$ MPa
(13)	Yamashita (Yamashita et al., 2003)	$\frac{\xi}{\xi_{iso}} = \left(\frac{\mu_w}{\mu_b} \right)^{0.72}$	HCFC22, $d=4.4$ mm, $P=5.5$ MPa, $G=700$ kg·m ⁻² ·s ⁻¹ , $q=0-60$ kW·m ⁻² , $H_b=225-395$ kJ·kg ⁻¹

Apparently, all of the nonisothermal flow correlations (as seen in Table 1) are built by introducing the ratio of thermo-physical properties, such as density, viscosity or both parameters, to improve the predicting performance of drag coefficient that is effected by steep variation of properties. However, the exponents for these correlations shown in Table 1 are different. In order to determine

the discrepancy among correlations, a group of experiment data has been selected and a detailed comparison for drag coefficient with six correlations from Eq. (8) to Eq. (13) has been conducted. The result is shown in Figure 3. The pressure of this case is 23 MPa, mass flux is $600 \text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ and heat flux is $300 \text{ kW}\cdot\text{m}^{-2}$.

Figure 3 A comparison of different drag coefficient correlations for nonisothermal flow, such as

Mikheev's, Popov's, Tarasova's, Razumovskiy's, Kirillov's, Yamashita's

It is found from Figure 3 that all the predicted profiles of drag coefficient are different at the same condition. Most of the calculated values predicted by various correlations present a similar variation along the bulk enthalpy except the curve obtained by Mikheev's correlation, where a maximum of ξ/ξ_{iso} appears at the enthalpy of $1348 \text{ kJ}\cdot\text{kg}^{-1}$. Interestingly, a drag coefficient "pit" was observed within the range of $1300\sim1800 \text{ kJ}\cdot\text{kg}^{-1}$ with the correlations from Eq.9 to Eq.13. The

calculated distribution of drag coefficient also shows large discrepancies among all of the above predicting equations. Hence, it is difficult to select an appropriate correlation for predicating drag coefficient of supercritical fluids flowing through smooth tubes in practical application.

Meanwhile, it is also found, from the literatures listed in Table 1, that the collecting measured results were mostly obtained from small-diameter tubes ($d < 4$ inch) (Kondrat'ev, 1969; Petrov and Popov, 1985; Razumovskiy et al., 2008; Tarasova and Leontev, 1968). With the increase of diameter, a relative greater contribution of the buoyancy and thermal acceleration will reinforce in the larger scale space and may affect/change the characteristic of the drag coefficients.

In order to understand the characteristics of drag coefficient in the circular channel under supercritical pressure, a series of experiments are performed to study the drag coefficients of supercritical water in horizontal smooth tubes with a wide range of operational parameters, such as the system pressures (P) ranging from 23 to 27 MPa, the average heat fluxes (q) varying from $100 \text{ kW}\cdot\text{m}^{-2}$ to $500 \text{ kW}\cdot\text{m}^{-2}$, and the mass fluxes (G) of water changing from 400 to $1000 \text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. In the present paper, the special minimum drag coefficient phenomenon is specially exhibited at first. Discussions and comparisons of the drag coefficients at the conditions with different mass fluxes, pressures and heat fluxes are further implemented. Based on the obtained drag coefficient data, two new drag coefficient correlations are respectively proposed for isothermal flow and nonisothermal flow by introducing the derivative of density with respect to temperature and Prandtl number, which can predict the resistance coefficient of supercritical pressure fluids with better accuracy than other existing correlations.

2. Experimental apparatus and procedure

In the present study, the platform of High Temperature and Pressure test loop (Hi-TaP) in Xi'an

Jiaotong University was used. The schematic diagram of the experimental test loop is shown in Figure 4. The working fluid made up of distilled and de-ionized water is pumped into the circulation system from a water tank by a high pressure piston pump. The water gains some heat when passing through a regenerative heat exchanger, and flows in a pre-heater to be heated further to reach the specified test conditions, and then flows into the test section. Both of the pre-heater and test section are electrically heated by alternative currents (in the range of 0–10,000A) with low voltages. The whole tube is thermally insulated by glass wool to minimize the heat loss. The water from the exit of the test section flows through the regenerator and the condenser, and then returns to the feed water tank. A mass flow meter is used to measure the mass flux of water. The water temperature at different locations are measured by NiCr–NiSi sheathed thermocouples.

1: Water tank; 2: Filter; 3: Water pump; 4: Valve; 5: Mass flow meter; 6: Heat exchanger;
7: Preheater; 8: Test section (including heated and adiabatic sections); 9: Condenser; 10:
Cooling water inlet; 11: Cooling water outlet

Figure 4 Schematic diagram of the Hi-TaP test loop

In our experiments, the two pressure drops method proposed by Kurganov (Kurganov et al., 2013) is applied. A smooth horizontal tube with $\Phi 32\text{mm} \times 3\text{mm}$ is adopted to avoid gravitational affection. The pressure drops in both heated and unheated parts are simultaneously measured. In order to get a fully developed flow, an adiabatic section with a length of $50 \times D$ is arranged in the upstream of heated section. In the test section, the layout of pressure measuring chamber and the wall temperature measuring points are installed on the outer surface are shown in Figure 5. A series of $\Phi 3\text{ mm}$ NiCr–NiSi armored thermocouples are protruded into the inlet and outlet of the test section to measure the bulk fluid temperatures. The fluid static pressure at the test section outlet is measured by Rosemount 3051 capacitance-type pressure transmitter. Meanwhile the pressure drops at both the heated section (DP1) and adiabatic section (DP2) are measured by 3051 capacitance-type differential pressure transducers. Then the measured signals are captured and transferred into the data-acquisition system. The uncertainties of all measuring variables are shown in Table 2.

Between the two test sections, a tube section with 150 mm interval is included to eliminate the disturbance of armored thermocouples to downstream adiabatic test section. Besides, it should be noted that the adapting two pressure drops method may make the flowing structure and temperature distribution at the outlet cross section of the heated tube (non-isothermal flow) greatly maintained to the adiabatic tube (isothermal flow). This means, at such conditions, the corresponding distribution of fluid parameters (i.e. velocity, temperature and turbulence energy)

coming from upstream nonisothermal section are transferred to the latter isothermal flow tube.

Figure 5 Experimental section and the measuring point disposition

Table 2 Uncertainties of measured and calculated variables

Variables	Uncertainty
Fluid temperature/ °C	0.195%
Wall temperature / °C	0.191%
Pressure /MPa	0.57%
Pressure drop /kPa	0.5%
Heat flux/kW·m ⁻²	3.25%
Mass flux/ kg·m ⁻² ·s ⁻¹	0.29%

2.1 Data processing

1) Non-isothermal Flow

In the heated tube, axial heat flux distributions are considered to be approximately uniform. Bulk fluid temperatures are usually measured in both inlet and outlet cross-sections, and the bulk

enthalpies and water temperatures at different local cross-sections are calculated with the heating balance method. Static pressure and pressure drop of the heated tube are directly measured by transmitter sensors, thus the corresponding drag coefficient can be evaluated by adapting the following conventional manner. As shown in Eq. (3), the corresponding frictional pressure drop can be accurately calculated by subtracting the accelerating pressure drop from the total pressure drop. The corresponding frictional pressure drop and drag coefficient can be obtained from the following equations.

$$\Delta P_{fri} = \Delta P_2 - \Delta P_{ac} \quad (14)$$

$$\xi = \frac{2\rho \times \Delta P_{fri} \times D}{G^2 \times L} \quad (15)$$

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2) Isothermal Flow

In the adiabatic section, it is assumed that the bulk temperature in cross section remain unchanged because the heat loss in the linkage segment between heated and adiabatic section is very tiny. The corresponding pressure drop due to flow acceleration can be ignored as a result of unchangeable density between inlet and outlet of test sections. Besides, the gravitational pressure drop almost have no effect in the horizontal tube and the local pressure drop equals zero. Hence, for the horizontal isothermal flow, the pressure drop and resistance factor can be simplified from the Eq. (1) into.

$$\Delta P_{tot} = \Delta P_{fri} \quad (16)$$

From Eq. (16), it is known that the resistance drop is actually the same with the measured experimental value, thus the drag coefficient can be got with the following equation.

$$\xi = \frac{2\rho \times \Delta P_{fr} \times D}{G^2 \times L} \quad (17)$$

3. Results and discussions

3.1 The phenomenon of the minimum drag coefficient

At first, the phenomenon of the minimum drag coefficient for supercritical turbulent flow is exhibited. Figure 6 shows the drag coefficient plotted against with Reynolds number at the pressure (P) of 25 MPa and mass flux (G) of $1000 \text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, together with the comparison results of experiment data and the calculated values by classical single-phase equations, such as Filonenko's (Eq.6), Nikuradse's (Nikuradse, 1933) (Eq.18), Blasius's (Eq.19) and Kondrat'ev (Kondrat'ev, 1969) equation.

$$1/\sqrt{\xi} = 2\log(\text{Re}\sqrt{\xi}) - 0.8 \quad (18)$$

$$\xi = \frac{0.184}{\text{Re}^{1/5}} \quad (19)$$

Figure 6 Comparisons of drag coefficients between calculated values obtained from Nikuradse, Blasius,

Filonenko, Kondrat'ev and experimental data for isothermal flow at different Reynolds number

(pressure is 25 MPa, and the mass flux is $1000 \text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)

It can be seen from Figure 6 that the experimental values of drag coefficients decrease firstly and then increases quickly with the increasing of Reynolds number. When the Reynolds number equal to 0.73×10^6 , the experimental drag coefficient reduced to a minimum value, which is hereafter called the minimum drag coefficient (MDC). Moreover, it is also found that the measured data are completely different from predicted results calculated by other classical equations for single phase flow. Large discrepancies exists between the measured and calculated drag coefficients. Therefore, we concluded that variations of the drag coefficients at supercritical pressures are absolutely different from that at room pressures. In other words, the drag coefficient formulas for single phase flow at room pressures could not be directly applied to supercritical pressure fluids.

Figure 7 exhibits a comparison result of drag coefficient between the experiment data and calculated values from Itaya correlation (Eq.6) and Filonenko equation (Eq.7) at different temperatures with the pressure of 23 MPa and the mass flux of $600 \text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, where the drag coefficient of isothermal flow and nonisothermal flow are respectively shown in Figure 7a and Figure 7b.

(a) Isothermal flow

(b) Nonisothermal flow

Figure 7 comparisons of drag coefficient between the experiment data and calculated values from Itaya correlation (Eq.6) and Filonenko equation (Eq.7) at different temperatures with the pressure of 23 MPa and the mass flux of $600 \text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$

It can be seen from both Figure 7(a) and Figure 7(b) that a “pit” appears near the pseudocritical point ($t_{pc}=377.5 \text{ }^{\circ}\text{C}$) and a minimum drag coefficient value of supercritical water emerges in both isothermal and nonisothermal flow. Although the change of Itaya's correlation (Eq.6) and Filonenko equation (Eq.7) are basically identical, both of the predicted values don't agree well with the experimental results, especially in the pseudocritical region. The maximum deviations are respectively reached to 57% and 64% for isothermal flow and nonisothermal flow. Therefore, further investigation on MDC should be carried out for better understanding this interesting phenomenon and a suitable predicting formula need to propose to fit for the experimental pressure drop data of supercritical flow. In the following sections, effect of heat flux, mass flux and pressure on drag coefficients for isothermal flow and isothermal flow are discussed respectively.

3.2 The drag coefficient of isothermal flow

3.2.1 Effect of heat fluxes

It should be noted that, for the adiabatic test section employed in our experiments, the heat fluxes adding on the test tube is actually equal to zero. The aim here is to find out whether the isothermal flow in the downstream is influenced by the flow of heated tube in the upstream or not. Figure 8 shows the variation of frictional pressure drop and drag coefficient with bulk enthalpy when the upstream heat fluxes change at the pressure of 23 MPa.

(a) frictional pressure drops of isothermal flow

(b) drag coefficients of isothermal flow

Figure 8 Variations of friction pressure drop (a) and drag coefficient (b) with bulk enthalpy at different

heat fluxes, where the heat fluxes are respectively 200, 300, 350 $\text{kW}\cdot\text{m}^{-2}$ and the pressure of 23MPa

and mass flux is $600 \text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$

From Figure 8, it is found that the pressure drops and drag coefficients at different heat fluxes are almost the same in the whole enthalpy regions, which indicate the upstream affection of non-isothermal flow ahead of the adiabatic test tube is very tiny and can be ignored. For the isothermal flow, when the bulk enthalpy is lower than $1800 \text{ kJ}\cdot\text{kg}^{-1}$, the pressure drop due to friction is close to the predicted result of Itaya correlation (Eq.6). But when the bulk enthalpy is higher than $1800 \text{ kJ}\cdot\text{kg}^{-1}$, the experimental data is significantly deviated from curve of Itaya and the “pit” gradually departs from the calculated value. The drag coefficient reaches a minimum value in the enthalpy of $2430 \text{ kJ}\cdot\text{kg}^{-1}$ ($t=382^\circ\text{C}$) after crossing the pseudocritical point ($t_{pc}=378^\circ\text{C}$, $H_{pc}=2204 \text{ kJ}\cdot\text{kg}^{-1}$) owing to a smaller density gradient recovering at such temperature point, as seen in Figure 1. When the bulk enthalpy is higher than $2500 \text{ kJ}\cdot\text{kg}^{-1}$, the corresponding friction pressure drop increases quickly because of the growing of “gas-like” fluid with low density. And the drag coefficients of isothermal flow in this region also present a fast increase too. Therefore, the results indicate that different heat fluxes added to the nonisothermal flow in the upstream of test section has basically no influence on the isothermal flow in the downstream.

3.2.2 Effect of pressures

Figure 9 shows the variation of friction pressure drop and drag coefficient with bulk enthalpy at different pressures, respectively.

(a) friction pressure drop

(b) drag coefficient

Figure 9 Variations of friction pressure drop (a) and drag coefficient (b) with bulk enthalpy at different

pressures ($P=23, 25, 27$ MPa), the mass flux (G) is $= 600 \text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ and the heat flux (q) is $300 \text{ kW}\cdot\text{m}^{-2}$

It can be seen from Figure 9 that experimental data of friction pressure drop and drag coefficient are both close to the Itaya predicting line when the enthalpy value is lower than $1800 \text{ kJ}\cdot\text{kg}^{-1}$.

Exceeding that bulk enthalpy point, the experimental points begin to be far from the Itaya predicting line. At different pressures, the given experimental data presents different characteristics, especially in the region of $2000\sim 2600 \text{ kJ}\cdot\text{kg}^{-1}$. The higher the pressures, the lower the minimum drag coefficient due to the reduced variation of thermal properties. The MDC equal to 0.76 at 23 MPa, but the value decreased to 0.5 when pressure increased to 27 MPa. The cause of these phenomena can be ascribed to the reduced variation of thermophysical properties with the pressure increasing. As seen in Figure 1, within the temperature range of $369\sim 385^\circ\text{C}$ (the corresponding bulk enthalpy ranges from $1800 \text{ kJ}\cdot\text{kg}^{-1}$ to $2500 \text{ kJ}\cdot\text{kg}^{-1}$), the thermophysical properties of supercritical fluids change less steeper with the pressure increases. When the pressure increases from 23 MPa to 27 MPa, the corresponding density decreases from 316 to $287\text{kg}\cdot\text{m}^{-3}$. Therefore, the drag coefficient “pit” becomes smaller with the increase of pressures.

3.2.3 Effect of mass flux

Figure 10 shows the frictional pressure drop and drag coefficient of unheated section with bulk enthalpy at different mass fluxes.

(a) friction pressure drop

(b) drag coefficient

Figure 10 Variations of friction pressure drops (a) and drag coefficients (b) with bulk enthalpy at different mass fluxes (G) (600, 800, 1000 $\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), the pressure (P) is 23MPa and heat flux (q) is

$$300 \text{ kW}\cdot\text{m}^{-2}$$

With the mass fluxes change from 600 $\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ to 1000 $\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, the corresponding friction pressure drops increase to a higher value due to the increase of flow velocity (or Reynold number).

Besides, all of the experimental data has a similar deviations with the calculating value of Itaya correlation. From Figure 10(a), it is found that the frictional pressure drops remain basically the same value in the low enthalpy region ($H_{\text{in}} < 1800 \text{ kJ}\cdot\text{kg}^{-1}$) under the same flow rate. Here the frictional pressure drops are approximately constant, 0.75 kPa at 1000 $\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ and 0.27 kPa at 600 $\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. When the enthalpies are higher than the enthalpy of 2400 $\text{kJ}\cdot\text{kg}^{-1}$, the flow resistance increased greatly due to the increase of velocity of the “gas-like” fluid with low density. Compared with friction pressure drop at different mass fluxes, it is known that the growths of pressure drops at high mass flux are more apparent and rapid than that at low mass flux. However, the comparison of the corresponding drag coefficients shows entirely different result compared to pressure drops, where almost all of the curves at different mass fluxes are basically overlapped, (see in Figure 10(b)). Mass fluxes have a tiny effect on the drag coefficient of isothermal flow.

3.3 The drag coefficient of non-isothermal flow

For nonisothermal flow, the bulk water temperature gradually rises along with tube length as a result of heating. The corresponding thermal properties changes with the bulk temperature as well. Thus an obvious difference of averaged temperature or density between inlet and outlet of the heated tube can be observed. During the process of heating, thermal acceleration is continually

increasing, which plays an important role and cannot be neglected. That means the whole pressure drop should be separated into two components, one caused by friction and the other formed by flow thermal acceleration. The corresponding drag coefficient can be obtained according to Eq. (17).

Figure 11 shows the variation of dimensionless frictional resistance coefficient (ξ/ξ_{iso}) of non-isothermal flow with bulk temperature, together with the results of correlations, such as Mikheev's (Eq.8), PoPov's (Eq.9), Tarasova's (Eq.10), Razumovs's (Eq.11), Kirillov's (Eq.12) and Yamashita's (Eq.13), where the ξ_{iso} has selected Filonenko correlation and variable " t_{avg} " is the integral-averaged value of the whole heated section.

Figure 11 comparisons of drag coefficients of non-isothermal flow between experimental data and predicating results obtained from Mikheev, Popov, Tarasova, Razumovs, Kirillov, Yamashita

It is shown that the dimensionless friction resistance coefficient (ξ/ξ_{iso}) fluctuates around 0.9 when the temperature is lower than 340°C, and then the value quickly decreases in the pseudocritical region, until reaches a minimum value at the pseudocritical point ($P=25\text{MPa}$, $t_{pc}=384^\circ\text{C}$). As depicted in Figure 11, all of the equations have a similar predicting trend except Mikheev's. But a large discrepancy exists in the predicting enthalpy location corresponding to the minimum ratio of drag coefficient owing to the differences in formulas. The predicted enthalpy location of the “pit” appears earlier than that got from experimental data. Furthermore, for different equations, the higher the power, the lower the MDC appears.

It is noteworthy that the difference between correlation predictions and experimental data might be influenced by tube diameter. As mentioned in the introduction part, most of the correlations are proposed on the basis of the smaller tube diameters ($d<4$ inch). With the increase of diameter, the buoyancy and thermal acceleration intensifies and strengthen the transverse flow in cross-sections of the tube.

3.3.1 Effect of heat fluxes

Figure 12 shows the variation of the drag coefficient for non-isothermal flow versus bulk enthalpy at different heat fluxes at pressure of 25 MPa and mass flux of $600 \text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. The predicted results of six dimensionless nonisothermal correlations was also presented and compared with experimental data at the heat flux of $200 \text{ kW}\cdot\text{m}^{-2}$.

Figure 12 Variations of drag coefficient with the averaged bulk enthalpy at different heat fluxes at 25MPa and $600 \text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, including $q=200, 300, 350 \text{ kW}\cdot\text{m}^{-2}$ and the predicted results of six dimensionless nonisothermal correlations compared with experimental data at the heat flux of $200 \text{ kW}\cdot\text{m}^{-2}$

It can be seen from Figure 12 that the experimental dimensionless drag coefficient (ξ/ξ_{iso}) is also varied around 0.9 and gets a minimum value near the pseudocritical enthalpy ($H_{\text{pc}}=2150 \text{ kJ}\cdot\text{kg}^{-1}$). With the heat flux increases, the ratio of ξ/ξ_{iso} gets a higher value before the pseudocritical point and obtains a lower value when the bulk enthalpy exceeds that point, which can be ascribed to increase of shear stress. At high-heat flux, the shear stress in the near wall region increases faster than that at low heat flux due to its high thermal acceleration **led by the reduction of density**. Thus the relative drag coefficient gets a much higher value than that at low heat flux. However, when the bulk enthalpy exceeds the pseudocritical point, the corresponding shear stress decreases due to **the reduction of thermophysical property's variation**, see Figure 1. Moreover, the ratio of

drag coefficients are always lower than 1.0, indicating that the drag coefficients of nonisothermal flow are lower than that of isothermal flow. This is because for nonisothermal flow with heating the effects of buoyancy and thermal acceleration are more remarkable. Comparison between measured and calculated drag coefficient distributions show that the experimental data does not well agree with the results of correlations, most of them capture the minimum resistance coefficient but considerably ahead of the experimental data. The Mikheev's equation is an exception, which introduces a ratio of Prandtl numbers to modify the effect of thermophysical properties. Although the prediction result of Mikheev's correlation is different from others, its distribution matches well with experimental data in the enthalpy region exceeding $1800 \text{ kJ}\cdot\text{kg}^{-1}$. This means that the Prandtl numbers maybe a good parameter for establishing new correlations for nonisothermal flow.

3.3.2 Effect of pressures

Figure 13 shows the variation of the friction resistance coefficients of non-isothermal flow with bulk enthalpy at different pressures with the heat flux of $300 \text{ kW}\cdot\text{m}^{-2}$ and the mass flux of $600 \text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. A comparison between calculated results of above six nonisothermal correlations and experimental data at pressure of 23MPa is also presented.

Figure 13 Variation of drag coefficient with bulk enthalpy at different pressures of 23, 25, 27 MPa at $G=600 \text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ and $q=300 \text{ kW}\cdot\text{m}^{-2}$ and a comparison between experimental data and calculated value with six correlations

It can be seen from Figure 13 that the pressure has a clear effect on the friction resistance, especially in the pseudocritical region. When the pressure is 23 MPa, the minimum value of ξ/ξ_0 is 0.38, but when the pressure increases to 27 MPa, the pit value turns into 0.64 owing to slow change of thermophysical properties at a higher pressure. For instance, the reduction of the density gradient with temperature ($\partial\rho/\partial T$), as seen in Figure 1, has been decreased from 41 to 18 $\text{kg}\cdot\text{m}^{-3}\cdot\text{K}^{-1}$. Similarly, in the aspect of the formula applicability, the MDC values calculated by correlations mismatch the measurement value. Besides, it can be found (see Figure 13), the pit of the experimental drag coefficient occurs around 2050 $\text{kJ}\cdot\text{kg}^{-1}$, which is also fallen behind the enthalpy point predicted by other formulas.

3.3.3 Effect of mass fluxes

Figure 14 depicts the variation of the friction resistance coefficient of non-isothermal flow with bulk enthalpy at different mass fluxes with pressure of 23 MPa and mass flux of $300 \text{ kW} \cdot \text{m}^{-2}$. It also shows a comparison with six nonisothermal correlations at mass flux of $600 \text{ kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$.

Figure 14 Variation of drag coefficient with bulk enthalpy at different mass fluxes, where the mass fluxes are respectively 600, 800, 1000 $\text{kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ at $P=23 \text{ MPa}$ and $q=300 \text{ kW} \cdot \text{m}^{-2}$

It can be seen from Figure 14 that the overall drag resistance ratio of supercritical water at different mass fluxes has a tiny change with the increase of bulk enthalpy even in the pseudocritical region ($1800 \sim 2400 \text{ kJ} \cdot \text{kg}^{-1}$). The experimental result of nonisothermal flow is similar to that of isothermal flow. The comparison results of different correlations also reveal an inconsistency with each other. In general, the calculated MDC value appear earlier in bulk enthalpy compared to the experimental data.

3.4 Difference between isothermal flow and nonisothermal flow

In order to understand the difference of isothermal flow and nonisothermal flow, Figure 15 shows a comparison between isothermal flow and nonisothermal flow in the horizontal tube with the pressure range of 23-27 MPa, the mass flux of 600-1000 $\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ and the heat flux of 200-300 $\text{kW}\cdot\text{m}^{-2}$.

Figure 15. The drag coefficient of isothermal flow vs. the drag coefficient of nonisothermal flow

It can be seen that the difference between isothermal flow and nonisothermal happens in the region lower than 1.06×10^{-2} . This critical value can be determined by in Figure 15. When the drag coefficient of isothermal flow is inferior to the critical value, the corresponding drag coefficient of non-isothermal flow is lower than that in the isothermal flow, which demonstrates that the drag coefficient at heating conditions is lower than that in the adiabatic tube. The reason can be ascribed to the enhancement of shear stress in the vicinity of heated wall. Along the heated section,

a steeper and greater variation of thermophysical properties occurs, the corresponding detailed flow information for nonisothermal flow, such as the structure and temperature fields in different cross-section, are changed faster than that of isothermal flow. However, when the resistance coefficient exceed 1.06×10^{-2} , the value of ξ_{iso} equals essentially to the coefficient of nonisothermal flow. In other words, both drag coefficients in the adiabatic and heated state are identical, due to the same change in thermal-physical properties. The above results reveal that thermophysical properties play a key role to the drag coefficients, especially for nonisothermal flow.

3.5 Development of New drag coefficient correlations

Based on the previously presented results for the drag coefficients of isothermal and nonisothermal flows, it was found that the investigated correlations considering the variation of the Reynolds number and ignoring the steep change of thermal properties around the pseudocritical region are inappropriate, because Reynolds number cannot fully represent the effect of steeply changing thermal properties. Thus a suitable correlation should be proposed for accurately predicting the friction resistance of supercritical fluid. In the present paper, based on existing correlations, a new variable of $\partial\rho/\partial T$ has been introduced to reduce the original deficiency of existing correlations. The new variable can hopefully represent the clear effect of steeply changing thermal properties at supercritical pressures around the pseudocritical region.

3.5.1 Correlation for isothermal flow

The Polynomial Regression Method (PRM) has been employed to establish new correlations, and the following new correlation for isothermal flow has been built by adding a correction term on

the basis of Filonenko correlation,

$$\xi = \frac{0.4976}{(1.82 \log_{10} Re_b - 1.64)^2} \left(-\frac{\partial \left(\frac{\rho}{\rho_c} \right)}{\partial \left(\frac{T}{T_c} \right)} \right)^{-0.1631}$$

Where, the subscript “c” presents the critical point of supercritical water, T_c and ρ_c is respectively equals 647.35 K and 322 kg/m³.

Figure 16 shows the comparison between experimental data and calculated results with different correlations. It can be seen from Figure 16 that the new correlation has a good agreement with experimental data for supercritical fluids, and it is much better than the classical Filonenko correlation for present experimental data.

Figure 16 Comparisons of experimental data and calculated results by new proposed correlation

3.5.2 Correlation for nonisothermal flow

A new correlation for non-isothermal flow is also proposed on the basis of existing previous

correlations, seen as follows. A comparison between the new proposed correlation and the previous formulae can be seen in Figure 17.

$$\frac{\xi}{\xi_{iso}} = 0.92248 \times \left(\frac{\rho_w}{\rho_b}\right)^{-0.01222} \times \text{Pr}_b^{-0.16277}$$

It can be seen in Figure 17 that the deviation of most of the points (93%) between the experimental data and calculated values is within the range of +/- 20%, which means that the new proposed correlation also has a good prediction for nonisothermal flow.

Figure 17 Comparison the results from existing correlations with the new proposed correlation

4. Conclusions

In the present paper, the phenomenon of the minimum drag coefficient at supercritical pressures, has been further investigated. The pressure drop and drag coefficient in both adiabatic section (isothermal flow) and heated section (non-isothermal flow) with horizontal arrangement have been

measured experimentally and analyzed systematically. The conclusions can be summarized as follows,

- 1) The phenomenon of the minimum drag coefficient appears in both the isothermal and nonisothermal flow. In the pseudocritical region, the drag coefficient shows a steep “pit”. This steep "pit" or minimum drag coefficient (MDC) cannot be accurately captured by existing correlations due to the fact that they do not consider properly the changing thermophysical properties especially in the pseudocritical region.
- 2) For the isothermal flow at supercritical pressure, the mass flux and heat flux have no effect on the drag coefficient distribution, but the pressure has significant effect owing to the weakened variation of thermal physical properties with the increase of pressures.
- 3) For the nonisothermal flow at supercritical pressure, the effect of pressure and mass flux is similar to the isothermal flow, but the effect of heat flux shows a complex behavior in the pseudocritical region. Before the pseudocritical transition, the higher the heat flux, the higher the drag coefficient. After the pseudocritical transition, the trend is the opposite: the higher the heat flux the lower the drag coefficient.
- 4) New correlations for predicting the drag coefficient in both isothermal and nonisothermal flow have been proposed considering the correction of thermophysical properties, which could lead to more accurate prediction of the resistance of the isothermal flow and nonisothermal flow.

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