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Effect of fluid temperature on the frictional coefficient of supercritical pressure water flowing in adiabatic horizontal tubes

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ABSTRACT

Based on the analysis on sensitivity of the frictional coefficient of supercritical pressure water to the fluid temperature, the conflict of the variation trends of the frictional coefficient with the fluid enthalpy obtained by different researchers was explained. It is shown that both concave curves and convex curves are reasonable for the variation trend of the frictional coefficient with the fluid enthalpy. For the same case, the variation trend of the frictional coefficient with the fluid enthalpy might change from concave curves to convex curves, or, from convex curves to concave curves, when the fluid temperature in the calculation of frictional coefficient is changed by a value as little as only 0.5–1.0 °C. The maximum error in the measured fluid temperature is estimated to be large enough (larger than ±1.0 °C), and might be the main reason for completely different tendencies of the frictional coefficient obtained in different studies.

1. Introduction

Supercritical fluids have been used widely as the working fluid in supercritical and ultra-supercritical pressure power plants boilers [1,2], the conceptually-designed supercritical pressure water-cooled reactors [3,4] and supercritical CO_2 Brayton cycle power systems [5,6]. Besides, supercritical fluids have also been used in other engineering applications, such as that in chemical engineering, refrigeration engineering and aerospace engineering [7–10]. Using supercritical pressure water (SCW) in power plants is the largest industrial application of supercritical fluids [11], since much higher thermal efficiency of the power plants is achieved when the live steam parameters (pressure and temperature) are increased to the supercritical parameters level. Investigation on the flow and heat transfer characteristics of supercritical fluids is extremely important to both the safe operation and the optimal design of the relevant systems.

The investigations on supercritical fluids have been extensively carried out since the 1950s, and the latest review work on hydraulic resistance to supercritical fluids flow was published by Pioro [12] and Kurganov [13], respectively. According to the review work of Pioro [12], the total pressure drop (ΔP_{tot}) for supercritical fluids flow in tubes consists of four components, including the pressure drop due to frictional resistance (ΔP_f), pressure drop due to local flow obstruction (ΔP_l), pressure drop due to thermal acceleration of flow (ΔP_a) and pressure drop due to gravity (ΔP_g), and can be calculated according to the following expression.

$$\Delta P_{tot} = \Delta P_f + \Delta P_g + \Delta P_a + \Delta P_l \quad (1)$$

The frictional pressure drop (ΔP_f) in experimental investigation was usually obtained by subtracting the other three pressure-drop components (see Eq. (1)) from the originally measured total pressure drop, since these three components can be directly calculated [12]. Based on the experimental data on the frictional pressure drop, the frictional coefficient, f, of supercritical fluids flow was generally calculated using the Darcy–Weisbach equation [12, 14–16], as follows.

$$f = \frac{2\Delta P_f \cdot D \cdot \rho}{L \cdot G^2} \quad (2)$$

where D is the tube diameter, L is the tube length, G is the mass flux, and ρ is the fluid density.

Investigation on the frictional coefficient of supercritical fluids is helpful for a deep insight into the mechanism of supercritical fluids flow, and it is also important for accurate prediction of frictional pressure drop in engineering applications. Frictional coefficient of supercritical fluids has been studied by several researchers, but these existing investigations were mainly focused on the development of correlations for frictional coefficient of supercritical fluids, in the form of a ratio of the frictional coefficient under heated conditions to that under isothermal conditions [15–20]. Detail review on the correlation for frictional coefficient of supercritical fluids can be referred to Pioro [12] and Kurganov

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Nomenclature

C_p	specific heat [kJ/(kg K)]
D	inside diameter [m]
f	frictional coefficient
G	mass flux [kg/(m^2 s)]
H	fluid enthalpy [kJ/kg]
h	heat transfer coefficient [W/(m K)]
L	tube length [m]
P	inlet pressure [MPa]
t	temperature [°C]
Greek symbols	
ρ	density [kg/m^3]
Φ	heat loss [W]
λ	thermal conductivity of insulating material [W/(m K)]
ΔP	pressure drop [kPa]
Δt	reduction value of the fluid temperature [°C]

Subscripts	
a	the pressure drop due to flow thermal acceleration
ave	average
f	frictional pressure drop
fo	air around the insulating layer
g	the pressure drop due to gravity
i	inside
l	the pressure drop due to local flow obstruction
o	outside
pc	pseudo critical
tot	total pressure drop
w	wall surface
Abbreviation	
SCW	supercritical pressure water

[13]. However, little work has been reported on the dependence of frictional coefficient of supercritical fluids on the fluid temperature (or enthalpy),[1] and no specific analysis on the frictional coefficient versus the fluid enthalpy relation was preformed in the review work of Pioro [12] and Kurganov [13] either.

The variations of frictional coefficient of supercritical fluids with fluid enthalpy (or temperature) obtained by different researchers are given in Fig. 1. Krasyakova [21] performed pressure drop experiments in a horizontal smooth tube under isothermal condition, and found that frictional coefficient of supercritical pressure water (SCW) decreases considerably to some minimum value and then increases gradually, as shown in Fig. 1(a), and the enthalpy at which frictional coefficients decrease was in the region near pseudo critical enthalpy.[2] That is to say, the curve of frictional coefficient with the fluid enthalpy (hereinafter called the "*f–H* curve") obtained by Krasyakova is a concave curve in the region near pseudo critical enthalpy. However, Wang [22] experimentally studied the frictional resistance to SCW flowing in the adiabatic horizontal ribbed tubes on the **Hi**gh **T**emperature **a**nd High **P**ressure two phase flow and heat transfer test loop at **X**i'an **J**iao**t**ong **U**niversity (Hi-TaP-XJTU), and found that a remarkable peak appears in the curve of frictional coefficient with fluid enthalpy in the pseudo critical enthalpy, see Fig. 1(b). That is to say, the *f–H* curve obtained by Wang is a convex curve. Besides, Zhu [23] experimentally studied the frictional resistance to supercritical kerosene RP-3 flowing in the adiabatic horizontal smooth tubes, see Fig. 1(c), and also found that a peak appears in the curve of frictional coefficient with fluid temperature in the region near the pseudo critical temperature. In addition, according to Zang's work [24], the experimental data on the frictional coefficient of SCW flowing in the vertically-upward heated smooth tubes were obtained in Nuclear Power Institute of China (NPIC), see Fig. 1(d), and it was found that the *f–H* curve obtained in NPIC was a concave curve in cases with upward heated conditions.

The above difference, even conflict, in results obtained by different researchers regarding the relationship between the frictional coefficient and the temperature (corresponding to enthalpy) of supercritical fluids has not yet been explained in open literature. The present paper is aimed to deeply understand the characteristics of the frictional coefficient of supercritical fluids, especially the special variation of frictional coefficient with the fluid enthalpy in the region near the pseudo critical enthalpy, and try to explain the existence of the above different tendencies of *f–H* curves. For this purpose, experiments for the frictional coefficient of SCW were carried out on the Hi-TaP-XJTU test loop. Based on the present experimental data and known data obtained by other researchers, effect of the fluid temperature was analyzed on the frictional coefficient of SCW. It should be noted that only the experimental data on the frictional coefficient of SCW flowing in adiabatic horizontal tubes was taken as an example in this paper to perform the analytical work, just because the pressure drop due to thermal acceleration of flow and the pressure drop due to gravity can be neglected in experiments with adiabatic horizontal tubes, and in this case the data about frictional pressure drop can be obtained directly and accurately.

2. Experimental procedure

The schematic diagram of the Hi-TaP-XJTU test loop is shown in Fig. 2. Detail information on the test loop and experimental methods can be seen in Ref. [25]. Here, a summary of nothing but the essential items of the system are introduced. The deionized water, as the working fluid, was boosted from the tank (1) by a high-pressure plunger pump (3). The pressure and the mass flux in the tests were adjusted by the main and bypass valves (4). After absorbing some heat of the hot fluid in the regenerative heat exchanger (6), the water was heated to a specific state in the preheating section (7). Then the heated water entered the adiabatic test section (8) for flow frictional resistance characterization. The water out from the test section (8) was cooled firstly by the above-mentioned heat exchanger and then by the condenser (9), and finally returned to the water tank.

A ribbed tube was used as the test section, and its mean inside diameter was 19.62 mm. The length of the test section was 2300 mm. The test section was installed horizontally without heating power input. The test tube and other heated tubes in the experimental system were all thermally insulated by glass wool.

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[1] The fluid temperature or enthalpy was generally adopted as the independent variable to represent the state of the fluid flowing in the tube for the study on the frictional resistance characteristics of supercritical fluids [12–15].

[2] Pseudo critical enthalpy H_{pc} (or pseudo critical temperature t_{pc}) is usually defined as a fluid enthalpy (or temperature) corresponding to the maximum value of the specific heat of the supercritical fluid at a given pressure [11].