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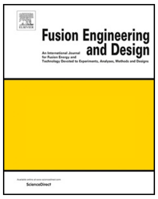

Experimental study on single-phase frictional pressure drop for water flow under high heat fluxes

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ABSTRACT

Pressure drop is one basic issue for the heat-removal systems for high heat flux components, such as the ITER divertors in fusion reactors, in which an accurate knowledge of single-phase frictional pressure drop is fundamental for further calculation of two-phase frictional pressure drop. However, the single-phase frictional pressure drop is still not well examined under high heat fluxes. In this study, experiments were conducted on the single-phase frictional pressure drop of water flow in circular tubes within the range of q = 5–10 MW/m^2, G = 6000–10,000 kg/m^2 s and p = 3–5 MPa (typical operating parameters for water-cooled divertors). The data were correlated using the equation of $f/f_{ad} = (\mu_w/\mu_b)^m$, in which m is an empirical exponent. It is found that the exponent m is affected by the length-to-diameter ratio of flow channel, while the effects of mass flux and heat flux are insignificant. In addition, a number of existing correlations for single-phase friction factor were compared with our data. The results indicate that these correlations cannot well capture part of the data. Therefore, a modified correlation is proposed to calculate the single-phase friction factor under high heat fluxes, in which the effect of length-to-diameter ratio is taken into account. The new correlation has an improved performance compared with the existing correlations.

1. Introduction

Heat removal technology is crucial for the ITER divertors that are subjected to extremely high heating fluxes with typical value of 10 MW/m^2 [1,2]. In recent years, many high-heat-flux removal technologies have studied for the ITER divertors, in which water-cooling technology has received much attention [3,4]. For the water-cooled divertors, the pressure drop of water flow in cooling structures is one of the most important thermal hydraulic issues [5,6]. Due to high heat fluxes, the pressure drop of subcooled boiling water flow (two-phase pressure drop) is commonly encountered [7,8]. Although two-phase pressure drop is the main concern in practical applications, single-phase pressure drop is still one basic issue, because the calculation of two-phase pressure drop is commonly based on the results of single-phase pressure drop.

In the open literature, there are already a large number of studies on single-phase frictional pressure drop under various conditions [9–13]. Although a large number of previous studies have successfully correlated single-phase frictional pressure drop, most of these studies are commonly used in adiabatic flow or conventional heating conditions [14–16].

For turbulent flow in an unheated channel, i.e., adiabatic flow, a number of empirical correlations can well predict the single-phase friction factor, in which the Blasius and the Filonenko correlations are most widely used. The Blasius correlation is expressed as $f_{ad} = 0.3164Re^{-0.25}$, and the Filonenko correlation is known as $f_{ad} = (1.82\lg Re - 1.64)^{-2}$. The valid ranges for Re of the two correlations are appropriately 5×10^3–10^5 and 4×10^3–10^{12}, respectively.

However, the single-phase flow in a heated channel, i.e., diabatic flow, is essentially different from adiabatic single-phase flow. Due to the heating effect, a temperature gradient is established between the heating surface and the bulk fluid, which affects the distributions of velocity and thermophysical properties (mainly viscosity). At the near-wall region, the temperature gradient reduces the viscosity but promotes the velocity gradient. The variations in viscosity and velocity have opposing effects on pressure drop. The former one decreases pressure drop while the latter one increases pressure drop. However, the viscosity effect is stronger, and diabatic pressure drop is usually lower than that in adiabatic flow. Moreover, the temperature gradient is steeper under higher heat fluxes, and the single-phase pressure drop decreases with increasing heat fluxes, as shown in Fig. 1.

Many researchers have investigated the diabatic single-phase flow

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Nomenclature

d	inner diameter, m
f	friction factor
G	mass flux, kg/m^2 s
H	enthalpy, J/kg
I	current, A
L	length, m
m	an empirical exponent
M	mass flow, kg/s
Nu	Nusselt number
p	pressure, MPa
Δp	pressure drop, Pa
Pr	Prandtl number
q	heat flux, W/m^2
Re	Reynolds number
T	temperature, °C
ΔT	heat-transfer temperature difference, °C
U	voltage, V

Greek symbols

η	thermal efficiency, %
μ	dynamic viscosity, kg/m s
ρ	density, kg/m^3

Subscripts

a	accelerational
ad	adiabatic
b	bulk
cal	calculated
exp	experimental
f	frictional
g	gravitational
H	heated
i	inlet
o	outlet
sat	saturation
tot	total
w	wall
ξ	local

and proposed empirical correlations for diabatic single-phase friction factor, in which some of these correlations are devoted to high-heat-flux applications. These correlations usually develop a friction factor ratio, f/f_{ad}, as a function of fluid-property ratio, in which the wall-to-bulk viscosity ratio, $\mu_{\mathrm{w}}/\mu_{\mathrm{b}}$, is mostly employed (Eq. (1)).

$$\frac{f}{f_{\mathrm{ad}}} = \left(\frac{\mu_{\mathrm{w}}}{\mu_{\mathrm{b}}}\right)^{m} \tag{1}$$

where f is friction factor under heating condition, and f_{ad} is adiabatic friction factor. μ_{w} and μ_{b} are viscosities based on wall temperature and bulk fluid temperature, respectively. The exponent m is an empirical coefficient. The typical correlations are summarized in Table 1.

Sieder–Tate [17] first used the Eq. (1) to correlate the single-phase pressure drop of oil flow under heating and cooling conditions. It was recommended that $m = 0.14$ for turbulent flow with heating. Tong et al. [18] performed experiments on the pressure drop with highly subcooled water flow in small tubes ($d = 1.05$–2.44 mm). They found that $m = 0.163$ was suitable for their data. Kays–Crawford [19] suggested $m = 0.25$ in Eq. (1). The same value was also adopted by Celata et al. [20]. They found a good agreement between the single-phase data obtained at high heat fluxes and the predictions using Eq. (1) with $m = 0.25$. Dormer–Bergles [21] experimentally studied the pressure drop of water flow in small tubes at high heat fluxes and low pressures. Their data were well-correlated using $m = 0.35$. Owens–Schrock [22] carried out an experiment of water flow in a vertical heated tube. They correlated the friction factor ratio using $m = 0.4$. Hoffman–Wong [23] developed a semi-empirical model to predict the pressure drop of subcooled water flow at uniform high heat fluxes. The exponent m was chosen as 0.3 in their model. However, the authors did not provide the basis for the selection.

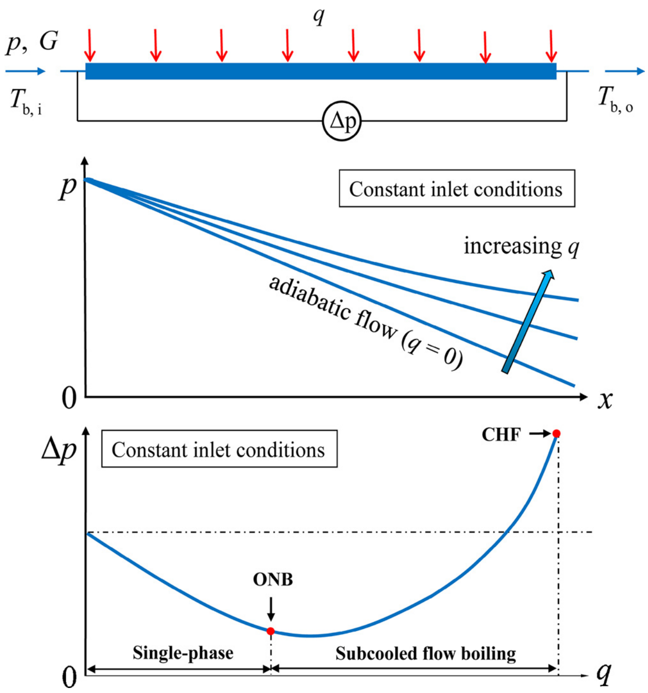

Fig. 1. General features of the distributions of p and Δp in a heated tube.

Maurer–LeTourneau [24] conducted experiments of water flow in a rectangular channel to determine friction factor with heat transfer at Reynolds numbers from 4×10^3–5×10^5. They observed that the flow rate and density had effects on friction factor, and proposed a correlation as $\frac{f}{f_{\mathrm{ad}}} = (\frac{\mu_{\mathrm{w}}}{\mu_{\mathrm{b}}})^{10 f_{\mathrm{ad}}} (\frac{\rho_{\mathrm{w}}}{\rho_{\mathrm{b}}})^{0.5}$. Petukhov [25] obtained a large number of experimental data for oil flow. The author proposed a differrent correction factor to represent the heating effect: $f/f_{\mathrm{ad}} = (7\text{-}\mu_{\mathrm{b}}/\mu_{\mathrm{w}})/6$. The application ranges were as follows: $Re = 10^4$–2.3×10^5, $\mu_{\mathrm{w}}/\mu_{\mathrm{b}} = 0.35$–$2$ and $Pr = 1.3$–10. It should be noted that the Petukhov equation could become negative because of the high value of $\mu_{\mathrm{b}}/\mu_{\mathrm{w}}$ under high heat fluxes.

In summary, although single-phase frictional pressure drop has been studied under various conditions, the effect of high heat fluxes on single-phase frictional pressure drop has not been well identified. Although the existing correlations of single-phase frictional pressure drop are sufficient for engineering applications, it is still expected to obtain a correlation that is more accurate under high-heat-flux conditions, because the correlation for two-phase frictional pressure drop is often based on single-phase correlation.

The present paper discusses the single-phase frictional pressure drop under high heat fluxes. Experiments were carried out to obtain single-phase frictional pressure drop of water flow in six vertical tubes under high operating parameters that were similar with those in the water