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Research Paper

Experimental study on the pressure drop characteristics of steam-water two-phase flow at a low mass velocity in a four-head rifled tube

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HIGHLIGHTS

- Pressure drop characteristic in rifled tube is studied at low mass velocity.
- Pressure and quality have influences on frictional pressure drop characteristics.
- Low two-phase frictional pressure drop ensures self-compensating characteristic.
- Empirical correlation is obtained for two-phase multiplier at low mass velocity.

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ABSTRACT

The pressure drop characteristics of steam-water two-phase flow at a low mass velocity in a four-head rifled tube were experimentally studied under an adiabatic condition with pressure ranging from 11.3 to 21.5 MPa, mass velocity ranging from 250 to 1200 kg/m^2 s, and steam quality ranging from 0 to 1. A test section composed of a 2000 mm long horizontal tube and 3500 mm long vertical tube was set up to fully evaluate the pressure drop characteristics, including the gravitational pressure drop and frictional pressure drop. It was found that the self-compensating characteristic is present in the four-head rifled tube when the mass velocity is lower than a certain critical value. The major parameters affecting the two-phase multiplier are pressure and steam quality. The two-phase multiplier increases with increasing steam quality and decreases with increasing pressure. In the near-critical pressure region, the two-phase frictional pressure drop approaches that of single phase flow because the density difference between water and steam is small. A new correlation for the two-phase multiplier for the frictional pressure drop of steam-water two-phase flow in the four-head rifled tube was proposed based on a total of 516 experimental data points, with a root mean square error of less than 20%. Comparing these results with previous correlations, the two-phase frictional pressure drop in the rifled tube is lower than those studied by previous scholars under low-velocity conditions, especially in the high steam quality region. The results provide instructive guidelines to improve the design and operational safety of a supercritical circulating fluidized bed boiler.

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1. Introduction and literature survey

The rifled tube is widely used in the power engineering field because it is one of the most effective and convenient technological devices to enhance heat transfer and restrain departure from nucleate boiling (DNB) [1–4] in large capacity heat exchangers. However, a rifled tube has intrinsic disadvantages compared to a smooth tube, such as a complex structure, a higher manufacturing cost and most importantly, a larger pressure loss under the same operating conditions. The large pressure loss in the water wall of a utility boiler or a nuclear reactor core leads to increased energy consumption of the feed water pump, creating issues of economic efficiency for the power station.

The frictional pressure drop for a fluid in a tube is presented in Eq. (1):

$$\Delta P = f \cdot \frac{l}{d} \cdot \frac{G^2}{2\rho} \tag{1}$$

where f is the friction factor, l is the tube length, G is the mass velocity of the flow, d is the hydraulic diameter of the tube and ρ is the

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Nomenclature

d	diameter, m
f	friction factor
Fr	Froude number
G	mass velocity, kg/(m^2 s)
l	length of tube, m
P	pressure, MPa
q	heat flux, kW/m^2
Re	Reynolds number
T	temperature, K
We	Weber number
x	steam quality

Greek letters

ρ	density, kg/m^3
Φ	two-phase multiplier
ψ	semi-theoretical coefficient
μ	dynamic viscosity, N s/m^2

Subscripts

av	average value
f	frictional
G	gas
g	gravitational
h	horizontal
in	inside
L	liquid
LO	liquid only
out	outside
max	maximum value
min	minimum value
SP	single phase
TP	two phase

average density of the flow. If the fluid is in the two-phase mode, the average density of the flow is given by Eq. (2):

$$\rho_{TP} = \frac{\rho_L}{1 + x \cdot \left(\frac{\rho_L}{\rho_G} - 1\right)} \tag{2}$$

where ρ_L and ρ_G are the density of saturated water and saturated steam, respectively, and x is the steam quality. The frictional pressure drop is primarily determined by the mass velocity of the flow for a tube with a fixed structure. Therefore, decreasing the mass velocity may be a good way to reduce frictional pressure drop. However, sufficient mass velocity guarantees the safety of the heating surface in a heat exchanger. To unite these two seemingly incompatible qualities, the Benson Vertical Tube (BVT) [5–7] is used in a supercritical circulating fluidized bed (SCFB) boiler to improve the heat transfer and hydrodynamic characteristics of the water wall at a low mass velocity (less than 1200 kg/m^2 s). BVT technology is based on the principle of the self-compensating characteristic (SCC, also called the natural circulation characteristic or the positive response characteristic) of parallel vertical tubes [8,9]. Using rifled tubes, supercritical once-through boilers can operate at low mass velocity within the water wall and achieve good hydrodynamic characteristics. During the heating process, the fluid frictional pressure drop within the vertical tube increases and the gravitational pressure decreases because the fluid density decreases. At a low mass velocity condition, the increment of the frictional pressure drop is less than the decrement of the gravitational pressure drop. This means that the total pressure drop in a vertical tube decreases at a low mass velocity condition during the heating process. For the vertical water wall, which is composed of parallel tubes, the tube that absorbs more heat (has higher heat flux) can always draw more fluid since its total pressure drop has the potential to decrease. Therefore, with the increased flow to the tube that absorbs more heat, the temperature rise at the tube's outlet is reduced, limiting the differential temperature between adjacent tubes of the vertical wall [8,10].

From the previous discussion, it is apparent that BVT technology is based on the special frictional pressure characteristics of a two-phase fluid in rifled tubes at a low mass velocity condition. Understanding the pressure drop characteristics of two-phase flow in a rifled tube at low mass velocity is necessary to improve this technology.

For single-phase flow, it has been proven that the Fanning formula and the Blasius formula for turbulent flow have good accuracy in predicting the frictional pressure drop [11–14]. For two-phase flow, the prediction methods for frictional pressure drop are usually empirical due to the intricate flow patterns and complex status parameters. Many classic empirical correlations have been proposed for two-phase flow in a smooth tube to improve the accuracy of the two-phase frictional pressure drop prediction, such as Martinelli et al. [15], Lockhart et al. [16], Bankoff [17], Chisholm [18], Friedel [19] and Beattie et al. [20]. However, these classic correlations are not suitable for a rifled tube because of its complex structural parameters. It is a commonly-held belief that there is no general two-phase frictional pressure drop correlation for every type of rifled tube. Consequently, it is necessary to propose a specific two-phase frictional pressure drop correlation for a specific rifled tube by modifying the two-phase frictional pressure drop models for smooth tubes [21].

Ackermann [22] reported the experimental results of pseudo-boiling of supercritical water in smooth and rifled tubes. It was found that the frictional pressure drop in a rifled tube is approximately 25% higher than that in a smooth tube. The increment of frictional pressure drop in a rifled tube has been explained by the strong centrifugal action caused by the inside ribs [23,24].

Köhler et al. [11] experimentally researched the frictional pressure drop of steam-water two-phase flow in a rifled tube. It was found that the frictional pressure drop in a rifled tube is twice as high as that in a smooth tube due to the effects of the internal ribs. The friction factor of a single phase is expressed by Eq. (3):

$$f = 1.01 \times 10^4 / Re^{1.2} + 0.0213 \tag{3}$$

and the two-phase multiplier is expressed by Eq. (4):

$$\Phi_{LO}^2 = (1-x)^2 + x^2(\rho_L/\rho_G)(f_G/f_L) + 6.0x^{1.2} \cdot (1-x)^{0.41} \cdot (\rho_L/\rho_G)(\mu_G/\mu_L)^{0.4}(1-\mu_G/\mu_L) \cdot Fr^{-0.05} \cdot We^{-0.033} \tag{4}$$

where μ_L and μ_G are the dynamic viscosity of saturated water and saturated steam. *Fr* is the Froude number and *We* is the Weber number, as defined by

$$Fr = G^2/(gd\rho_L^2) \tag{5}$$

$$We = G^2 d/(\rho_L \sigma) \tag{6}$$

where σ is the coefficient of surface tension.

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