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Frictional resistance of adiabatic two-phase flow in narrow rectangular duct under rolling conditions

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ABSTRACT

Frictional resistance of air-water two-phase flow in a narrow rectangular duct subjected to rolling motion was investigated experimentally. Time-averaged and transient frictional pressure drop under rolling condition were compared with conventional correlation in laminar flow region ($Re_l < 800$), transition flow region ($800 \leqslant Re_l \leqslant 1400$) and turbulent flow region ($Re_l > 1400$) respectively. The result shows that, despite no influence on time-averaged frictional resistance, rolling motion does induce periodical fluctuation of the pressure drop in laminar and transition flow regions. Transient frictional pressure drop fluctuates synchronously with the rolling motion both in laminar and in transition flow region, while it is nearly invariable in turbulent flow region. The fluctuation amplitude of the Relative frictional pressure gradient decreases with the increasing of the superficial velocities. Lee and Lee (2002) correlation and Chisholm (1967) correlation could satisfactorily predict time-averaged frictional pressure drop under rolling conditions, whereas poorly predict the transient frictional pressure drop when it fluctuates periodically. A new correlation with better accuracy for predicting the transient frictional pressure drop in rolling motion is achieved by modifying the Chisholm (1967) correlation on the basis of analyzing the present experimental results with a great number of data points.

1. Introduction

With the extensive application of nuclear power system in marine transportation, effects of ocean condition (rolling, heaving, pitching, inclination etc.) on a flow and heat transfer system have attracted growing interests in recent years. From a fluid mechanics point of view, the main difference between land-based and barge-mounted equipment is that the latter is inevitable from the effect of sea wave shocks and winds (Ishida et al., 1995). The thermal hydraulic behavior of shipborne equipment is influenced by rolling, heaving and pitching motions, leading to the occurrence of unsteady flow as mentioned by Pendyala et al. (2008) and Tan et al. (2009a).

A number of previous studies regarding single-phase flow behaviors under ocean condition have been performed in recent years. Studies of Gao et al. (1997), Ishida and Yoritsune (2002), Murata et al. (2002), Tan et al. (2009a,b) and Yan and Yu (2009) indicated that the flow rate of a natural circulation system will oscillate sinusoidally in rolling motion, whereas almost keeps constant for a forced circulation loop. Rolling parameters, flow rates and the component layout in the experimental loop have strong effects on the thermal hydraulic behavior of a natural circulation system. Cao et al. (2006), Xing et al. (2012) and Zhang et al. (2009) performed a series of experiments to investigate the effect of rolling parameters, flow rates and tube radius on single-phase forced circulation in pipes. Their results indicated that the frictional pressure drop of single-phase flow oscillates periodically in rolling motion. New empirical correlations for calculating the single-phase friction factor in rolling pipes were achieved from their experimental data. Studies of Pendyala et al. (2008) indicated that heaving movement can lead to the fluctuation of a forced single-phase flow. The mean friction factor in heaving motion was considered to be greater than that under immobile condition. Yan et al. (2010, 2011) gave the velocity distribution of single-phase flow in tubes under rolling condition, and showed that rolling motion influences only the velocity distribution near the channel wall but not influence its mean frictional resistance. From afore-mentioned work, it is clear that the single-phase fluid flow in an oscillating pipe is rather different from that in a pipe at rest. However, few related studies deal with two-phase flow characteristics in rolling motion, and the summarizations are listed as follow.

Cao et al. (2006) studied the frictional resistance of single-phase and two-phase flow in pipes under rolling condition, and demonstrated that the predicted friction factor by traditional correlations deviates dramatically from the experimental results. They also proposed a new correlation according to homogeneous flow model.

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Nomenclature

General symbols

f	rolling frequency (Hz)
T	rolling period (s)
t	time (s)
θ_m	rolling amplitude (rad)
ΔP_t	total pressure drop (kPa)
ΔP_f	frictional pressure drop (kPa)
ΔP_g	gravitational pressure drop (kPa)
ΔP_{add}	additional pressure drop (kPa)
$\Delta\rho$	density difference between phases (kg/m^3)
$\bar{j}$	time-averaged superficial velocity (m/s)
g	gravity acceleration (m/s^2)
L	length between pressure taps (m)
h	height of the duct (m)
w	width of the duct (m)
j	superficial velocity (m/s)
dP_f/dz	two-phase frictional pressure gradient (kPa/m)
ΔP	pressure drop (kPa)
$d(P_f)_g/dz$	gas frictional pressure gradient (kPa/m)
$d(P_f)_g/dz$	liquid frictional pressure gradient (kPa/m)
ϕ_1^2	frictional multiplier factor, Eq. (11)
x	mass quality
X	Martinelli parameter, Eq. (13)
U_0	rolling velocity, Eq. (20) (m/s)
l	the distance between the test section and the rolling shaft (m)
Re	Reynolds number ($Re = jd_e/\gamma$)
d_e	hydraulic diameter of the test section (m)

Greek letters

θ	rolling angle (°)
ω	angular velocity (rad/s)
β	angular acceleration (rad/s^2)
ρ	fluid density (kg/m^3)
α	void fraction
ε	ratio of duct height to width ($\varepsilon = h/w$)
γ	kinematic viscosity (m^2/s)
μ	dynamic viscous (Pa s)
σ	surface tension (N/m)
λ	single-phase friction factor

Subscripts

roll	under rolling condition
g	gas phase flows alone through the same pipe with its mass flow rate
l	liquid phase flows alone through the same pipe with its mass flow rate
$l0$	liquid phase flows only through the same pipe with total mass flow rate
1, 2	start and end points
pred	prediction
exp	experiment

Superscript

$'$	relative coordinate

The time-averaged frictional resistance of bubbly flow in rolling motion was predicted by their correlation with an accuracy of ±25%. The effects of rolling motion on air-water two-phase flow pattern transition were investigated experimentally by Luan et al. (2007) and Zhang et al. (2007). Their results showed that the rolling period, rolling amplitude and channel size affect the transitions between flow patterns, especially from the bubble to slug flow and churn to annular flow. Yan et al. (2008) measured the volume-averaged void fraction at a certain rolling angle with the help of quick-closing valves method. The result showed that rolling motion results in the decrease of the void fraction, but no correlation for such a condition was achieved. Tan et al. (2009c) experimentally studied the two-phase flow instability of natural circulation under rolling condition, and their result indicated that rolling motion causes the early occurrence of two-phase flow instability.

The above reviewed researches regarding two-phase flow behavior in rolling motion were all performed for circular tube, whereas frictional resistance in narrow rectangular duct under rolling condition has not been studied in detail so far. In addition, none of the above work gives the transient frictional pressure drop. With demands for higher heat transfer efficiency and less space requirement in practical applications, rectangular duct is one of the choices as the heat transfer tube in a compact heat exchanger. Therefore, researches on thermal hydraulic characteristics of two-phase flow in narrow rectangular ducts have been received increasing attention over the last few decades (Lee and Lee, 2002; Ma et al., 2010; Mishima et al., 1993; Sadatomi et al., 1982; Wang et al., 2011a; Zhou and Wang, 2011). Most studies on two-phase flow resistance in narrow ducts are concerning motionless condition, few can be found in rolling motion. Wang et al. (2011b) investigated two-phase flow patterns under rolling conditions and obtained the flow pattern map for a narrow rectangular duct having cross section of 40 mm × 1.6 mm. Recently, Hong et al. (2012a,b) and Wei et al. (2011) studied the onset of nucleate boiling and the bubble behaviors in subcooled flow boiling under ocean condition. According to the authors' knowledge, the frictional resistance of two-phase flow in rectangular duct under rolling condition has not been studied carefully. To better understand the effect of rolling motion on two-phase flow resistance, a series of experiments was performed by using a narrow rectangular duct having cross section of 43 mm × 1.41 mm. The effects of rolling motion on time-averaged and transient frictional pressure drop were investigated in different flow regions.

2. Experimental apparatus

2.1. Description of the rolling platform

The rolling movement of a ship was simulated by a simple harmonic motion. The rolling platform, a 2.5 m × 3.5 m rectangular plane, rotates with the central shaft (O–O) as shown in Fig. 1. Rolling movement with required rolling period and amplitude is controlled by an automatic system (Wang et al., 2011b; Xing et al., 2012). Consequently, the rolling amplitude could be expressed as follow:

$$\theta = \theta_m \sin(2\pi ft) \tag{1}$$

Clockwise direction is defined as the positive direction of the rolling movement as shown in Fig. 1. Accordingly, the angular velocity and angular acceleration are deduced as follow:

$$\omega = 2\pi f\theta_m \cos(2\pi ft) \tag{2}$$

$$\beta = -4\pi^2 f^2 \theta_m \sin(2\pi ft) \tag{3}$$