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Effect of rolling motion on two-phase frictional pressure drop of boiling flows in a rectangular narrow channel

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ABSTRACT

In order to investigate the two-phase frictional pressure drop characteristics of boiling flow in a rectangular narrow channel under rolling motion, a series of experiments and theoretical analysis are performed. The results demonstrate that the total additional pressure drop fluctuation has the same period with the rolling motion, and the fluctuation amplitude increases with the increase of rolling amplitude and rolling frequency. The time average additional pressure drop is 2–3 orders of magnitude smaller than that of frictional pressure drop in the boiling region. The fluctuation amplitude of the two-phase frictional pressure drop increases with increasing rolling amplitude, rolling period and heat flux, while it decreases with the increase of system pressure. Compared with the additional pressure drop in two-phase regions the outlet quality of channel and the space variation of the experimental loop are the main reasons that induce the fluctuation of two-phase frictional pressure drop. The mass flux fluctuation varies with the fluctuation of two-phase frictional pressure drop, and the fluctuation amplitude of mass flux increases with the increase of rolling amplitude and rolling period. The phase lag between the fluctuation of mass flux and frictional pressure drop is approximately equal to 1/4 rolling period.

1. Introduction

In recent years, with the rapid development of nuclear technologies, nuclear power systems are extensively applied in marine fields, and the effects of ocean conditions (rolling, pitching, heaving, inclination etc.) on the flow and heat transfer system have attracted growing interests. The main difference between land-based and barge-mounted equipment is the influence of sea wave oscillations on the latter (Ishida et al., 1990, 1995). The thermal hydraulic behavior of barge-mounted equipment is influenced by the rolling, pitching, and heaving motions, those motions will lead to the occurrence of unsteady flow as mentioned by Pendyala et al. (2008) and Gao et al. (1999).

Recently, a number of experimental and numerical studies regarding single-phase flow behaviors under ocean condition have been performed under both natural and forced circulation conditions. Studies of Ishida and Yoritsune (2002), Murata et al. (2002), Tan et al. (2009a,c), Yan and Yu (2012) indicated that the additional inertial force caused by rolling motion easily causes the natural circulation flow to fluctuate, and with the increase of rolling amplitude and frequency the average mass flow rate of natural circulation will decrease, whereas, the heat transfer coefficient increases with the increase of rolling amplitude and frequency. The results also indicated that the rolling parameters, mass flow rates and the component layout in the experimental loop have strong effects on the thermal hydraulic behavior of a natural circulation system. Xing et al. (2012, 2013a) and Wang et al. (2014a) performed a series of experimental researches to investigate the effects of rolling amplitude, rolling period, flow rates, and driving head on the flow characteristics of single-phase forced circulation. Their results also indicated that the flow rate and frictional pressure drop of single-phase flow oscillates periodically in rolling motion. New empirical correlations for calculating the single-phase friction factor under rolling motion were developed based on their experimental data. The effect of oscillations on the flow resistance in a vertical tube has been studied experimentally by Pendyala et al. (2008), their results indicated that the heaving motion can lead to fluctuation of a forced single-phase flow. The time average friction factor under heaving motion was considered to be greater than that under steady state. The effect of additional inertial forces on the pulsating flow under rolling motion condition was theoretically and experimentally studied by Wang et al.

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Nomenclature

a_{ce}	centripetal acceleration (m/s^2)
a_{co}	Coriolis acceleration (m/s^2)
a_{ta}	tangential acceleration (m/s^2)
A	rolling angle (°)
F	force (N)
g	gravitational acceleration (m/s^2)
G	mass flux (kg/m^{2}s)
h	distance between two pressure tubes (m)
L	length of channel (m)
p	system pressure (MPa)
Δp_{tp}	two-phase pressure drop (kPa)
q	heat flux (kW/m^2)
t	time (s)
T	rolling period (s)
x_e	thermodynamic equilibrium quality

Greek symbols

β	angular acceleration (rad/s^2)
$\theta_{\max}$	maximum rolling amplitude (°)
ρ	density (kg/m^3)
ω	angular velocity (rad/s)

Subscripts

ave	time average value
acc	acceleration
c	cooling fluid
exp	experimental (measured)
f	friction
h	hot fluid
max	maximum
min	minimum
tp	two phase

(2014b) and Xing et al. (2013a), their results indicated that the relative pulsation amplitude of flow rate increases with the increase of driving head, however, it decreases with increasing experimental loop friction resistance. The effect of additional inertial force can be neglected and the flow rate will not present significant pulsation when the intensity of the driving force is 10 times larger than the additional inertial force. The results also show that the intensity of flow rate fluctuation under rolling motion mainly depends on the relative quantity of driving head, friction resistance and additional inertial force. The effects of several parameters on the velocity profile in the cross section are investigated by Yan et al. (2010a,b), Yan and Gu (2011). The rolling amplitude and period only affect the velocity in a specified proportion, and the velocity profile shape remains unchanged. The rolling period, tube radius, and fluid viscosity not only affect the velocity peak, but also the profile shape. The fluid viscosity and rube radius could limit the effect of rolling on the flow.

From aforementioned work, it is clear that the flow characteristic of single-phase flow under rolling motion is rather different from that under steady state. However, few related studies deal with the two-phase flow characteristics under rolling motion, and the summarization is listed as follows. Xing et al. (2013b) studied the frictional resistance of adiabatic two-phase flow under rolling conditions. Their results indicated that the rolling motion induces the periodical fluctuation of the pressure drop in laminar and transition flow regions. Instantaneous frictional pressure drop fluctuates synchronously with rolling motion. The fluctuation amplitudes of the frictional pressure gradients decrease with the increase of superficial velocity. Experimental study of the characteristics of air–water mixture flow resistance under rolling motion condition was carried out by Jin et al. (2014a,b). The instantaneous frictional pressure drop strongly depends on the mass quality, Reynolds number, rolling period and amplitude. Based on those parameters, a new correlation for predicting the friction factor was developed. Numerical research on two-phase instability in multi-channels under rolling motion was performed by Zhang et al. (2011), the result indicated that the system will become more unstable with the increase of rolling amplitudes, the critical power and system instability will appear ahead of time since the rolling motion. In the low equilibrium quality region, the system stability is intensified with the increase of heating power. While in the high equilibrium quality region, increasing the heating power can weaken the system stability. Similar experimental results were proposed by Tan et al. (2009b) who performed a series of experimental study on two-phase flow instability under rolling motion condition.

The above reviewed researches regarding two-phase flow behavior under rolling motion were mainly performed for adiabatic air–water mixture flow and flow instability in a circular tube. Whereas, frictional resistance of boiling flow in a rectangular narrow channel under rolling motion have not been studied in detail so far. In addition, none of the above work gives the instantaneous frictional pressure drop. With demands for high heat transfer performance and less space requirement in practical applications, compact heat exchangers are widely used. Mostly, a compact heat exchanger is composed of an array of rectangular narrow channels with the small gap size (Lee and Lee, 2001). Therefore, researches on thermal hydraulic characteristics of two-phase flow in a rectangular narrow channel have been received increasing attention over the last few decades (Ishibashi and Nishikawa, 1969; Mishima et al., 1993; Tran et al., 1996; Chen et al., 2009; Sun and Mishima, 2009; Kim and Mudawar, 2013; Farahani et al., 2014). Most studies on two-phase flow resistance in narrow ducts are concerned motionless condition, few can be found under rolling motion conditions. In order to better understand the effect of rolling motion on two-phase flow resistance, a series of experiments were performed by using a rectangular narrow channel with the inner size of 2 mm × 40 mm. The effects of rolling motion on instantaneous and time average frictional pressure drop were investigated.

2. Experimental apparatus

The rolling movement of a ship was simulated by a mechanical rolling thermal-hydraulic experimental apparatus, and the detail description of the experimental setup can be found in the earlier publication proposed by Chen et al. (2015). The experimental facility is comprised of an experimental loop, an instrument system, and a rolling motion driven mechanism.

2.1. Experimental loop and instruments

The mechanical rolling thermal-hydraulic experimental facility is schematically illustrated in Fig. 1, and the maximum mass flow rate is 3 m^3/h, the maximum system pressure is 3 MPa. The experimental loop is composed of a hot loop and a cooling loop, the