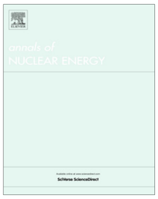
Annals of Nuclear Energy 64 (2014) 135–143

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene



Effect of rolling motion on transient flow resistance of two-phase flow in a narrow rectangular duct

Guangyuan Jin, Changqi Yan *, Licheng Sun, Dianchuan Xing

National Defense Key Subject Laboratory for Nuclear Safety and Simulation Technology, Harbin Engineering University, Harbin 150001, China

A R T I C L E   I N F O

Article history:
Received 14 May 2013
Received in revised form 17 September 2013
Accepted 19 September 2013
Available online 20 October 2013

Keywords:
Rolling motion
Frictional factor
Narrow rectangular duct
Pressure drop

A B S T R A C T

As a typical ocean environment, rolling motion can induce additional forces on a flow system. Experimental study of the characteristics of air–water mixture flow resistance in narrow rectangular channel($40 \times 1.41\ \mathrm{mm}^2$) in rolling motions was carried out with the rolling periods and amplitudes of 8 s, 12 s, 16 s, and 10°, 15°, 30°, respectively. Several homogeneous and separated flow models were evaluated against the experimental data to clarify their applicability in predicting the two-phase flow resistance in vertical rectangular channels. The comparison showed that McAdams correlation for calculating the viscosity in homogeneous model is suitable for the present situation to calculate the averaged two-phase flow resistance. Transient flow resistance under rolling condition changed periodically, as a result, attempt was conducted to illustrate the effect of rolling motion. Transient frictional pressure drop strongly depends on the mass quality, Reynolds number, rolling period and amplitude. The fluctuation amplitude of the frictional pressure drop increased with increasing mass quality and rolling amplitude. It also increased with reduction of the rolling period. A new correlation for predicting the transient frictional factor was given by including the influence of rolling parameters and was validated against the experimental data.

1. Introduction

Two-phase flow is frequently met in more and more fields such as chemical engineering, refrigeration and nuclear power systems. How to predict the pressure drop of two-phase flow has been an important subject over several decades. Theoretical and experimental researches on two-phase flow pressure drop have been carried out since 1940s, aiming at finding an universal prediction method for engineering applications. A preliminary study showed that under steady condition, the two-phase flow pressure drop could be affected by more than a dozen parameters due to its complexity. Most of the related studies are focused on experienced correlations with several designated parameters, which might be more complex and difficult to acquire for unsteady condition because of more parameters involved.

Thermal–hydraulic behaviors involved barged-mounted power plant attracted a growing interest in recent years, as sea wave induced ship motions, such as rolling, heaving, and pinching, can result in the change of momentum, heat and mass transfer therein (Pendyala et al., 2008). Theoretical model of the natural circulation in nuclear systems under ocean environment was firstly proposed by Pang et al. (1995). Rolling motion, as a typical behavior of ocean environment, was of interest in recent year. Gao et al. (1997), Murata et al. (2002) and Tan et al. (2009a,b) found that the flow rate of a natural circulation system fluctuated periodically in rolling motion, but kept invariable for a forced circulation loop. The study of Cao et al. (2007) indicated that the rolling period, rolling amplitude and mean Reynolds number could influence the frictional characteristics of single-phase flow. Experiments were carried out by Yan and Yu (2009) to investigate the effect of rolling motion on single-phase flow characteristics. They worked out the solution of momentum conservation equation for an entire loop. Yan et al. (2010a, 2011a,b,c,d) established a theoretical model for single flow inside tubes under rolling condition, and their simulation result showed a good agreement with the experimental data. Xing et al. (2012) investigated the effects of Reynolds number, rolling period and rolling amplitude on frictional pressure drop experimentally and also proposed a simple one-dimensional analytical model to clarify the effect of pressure head on the fluctuation of flow rate. These researches mentioned above showed that the rolling period, rolling amplitude, channel size and pressure head may affect the characteristics of single-phase frictional pressure drop under rolling motion, but very few researches dealt with that of two-phase flow.

Researches on thermal–hydraulic behaviors in micro- and mini-channels have been received increasing attention over the last few decades because of their high heat-transfer performance (Lee and

---

* Corresponding author. Tel./fax: +86 451 82569655.
E-mail address: changqi_yan@163.com (C. Yan).

0306-4549/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.anucene.2013.09.035

Nomenclature

General symbols

T	rolling period (s)
t	time (s)
L	length between the pressure taps (m)
D	hydraulic diameter of test sections (m)
$\underline{Re}$	the two-phase Reynolds number
Re	the two-phase mean Reynolds number in the several complete periods
Δp	measured pressure drop (Pa)
Δp_a	acceleration pressure drop (Pa)
Δp_{add}	additional pressure drop (Pa)
Δp_f	frictional pressure drop between pressure taps (Pa)
Δp_g	gravitational pressure drop (Pa)
G	mass flow velocity (kg/s m^{-2})
l	the distance between the test section and rolling axis (m)
s	the gap of the test section (m)
w	the width of the test section (m)
V	two phase mixture velocity (m/s)

Greek letters

θ	rolling angle (rad)
ω	angular velocity (rad/s)
β	angular acceleration (rad/s^2)
ρ	the mixture density (kg/m^3)
γ	kinematic viscous (m^2/s)
λ	Darcy frictional coefficient
μ	dynamic viscous (Pa s)
ξ	the volumetric quality (–)
ϕ^2	the two-phase frictional multipliers
χ	aspect ratio for the duct, (χ = height/width)

subscripts

m	the maximum value
l	liquid
g	gas
0	non-rolling condition
tp	two phase flow
roll	under rolling condition
pred	the predicted value
exp	experimental value

Lee, 2001; Mishima and Hibiki, 1996; Sun and Mishima, 2009; Zhang et al., 2010). Behavior of gas and liquid flow in narrow channels were studied by Mishima and Hibiki (1996), whereby a correlation for predicting the frictional pressure drop was acquired to account for the effect of the channel sizes. The Lee and Lee correlation (2001) was set up against 305 experimental data points of horizontal rectangular channel with small heights, and also Sun and Mishima (2009) proposed a new correlation against a more complete dataset with 2092 data points, covering the range of hydraulic diameter from 0.506 to 12 mm. Zhang et al. (2010) evaluated 10 correlations based on separated flow approach against a variety of experimental data sets, among which the Zhang et al. correlation (2010) and Mishima–Hibiki correlation (1996) had the best accuracy. However, though the correlations aforementioned are, without exceptions based on the separated flow model, some researchers (Chen and Yang, 2002; Choi et al., 2011; Triplett and Ghiaasiaan, 1999) found that in micro-channels, homogeneous flow model could be well used, to which more attention should be paid.

In this paper, we focus on the effect of rolling motion on transient flow frictional resistance of two-phase flow, and try to develop a correlation for predicting the frictional resistance of two-phase flow in rolling motions.

2. Experiment

2.1. Description of the rolling platform

The experimental loop was fixed on a platform (2.5 m × 3.5 m rectangular plane) which could roll with its central shaft in a specified rolling period and amplitude. The platform is driven by fluid power controlled by a specially designed control system. Fig. 1 shows the side view of the rolling platform, a positive rolling angle is defined as which the rotation is counterclockwise viewed from the front of the test section. The frictional pressure drop of two-phase flow under steady condition could be acquired when the rolling platform is in a fixed position. The rolling movement was simulated following the discipline of trigonometric function. The rolling amplitude can be expressed as follows:

$$\theta = \theta_m \sin(\omega_0 t) = \theta_m \sin\left(\frac{2\pi}{T}t\right) \tag{1}$$

Thus, the angular velocity and acceleration of the rolling motions are deduced as follow:

$$\omega = \frac{d\theta}{dt} = \theta_m \frac{2\pi}{T} \cos\left(\frac{2\pi}{T}t\right) \tag{2}$$

$$\beta = \frac{d\omega}{dt} = -\theta_m \left(\frac{2\pi}{T}\right)^2 \sin\left(\frac{2\pi}{T}t\right) \tag{3}$$

where θ_m and T denote the rolling amplitude and the rolling period, respectively, the rolling conditions are: $\theta_m 10°T8s$; $\theta_m 10°T12s$; $\theta_m 10°T16s$; $\theta_m 15°T16s$; $\theta_m 30°T16s$. (θ_m-rolling amplitude T-rolling period)

2.2. Experimental loop and measuring method

The schematic diagram of the experimental loop is shown in Fig. 2. The test section is a rectangular duct made of transparent acrylic resin. The width and length of the test section are 40 mm and 2000 mm respectively. The gap, s, is fabricated with the size of 1.4 mm, which is confirmed by using the theoretical correlation of the friction factor for laminar flow in rectangular ducts and the experimental data (Shen et al., 2012). The frictional resistance

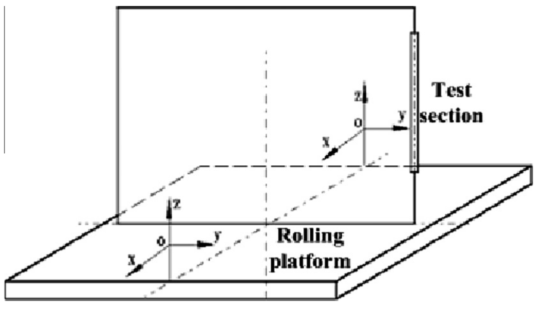


Fig. 1. Side view of rolling platform.