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Resistance characteristics of air–water two-phase flow in a rolling 3 × 3 rod bundle

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ABSTRACT

Experimental investigation on ambient air–water two-phase flow in a 3 × 3 rod bundle subjected to rolling motion was carried out. Time-averaged and transient frictional resistance in rolling motion were studied in detailed. The results indicate that although time-averaged flow rate and frictional pressure drop in rolling rod bundle are very close to that under steady vertical condition, rolling motion induces obvious transient periodical fluctuation of frictional pressure gradient at low gas and liquid flow rate. While the periodical fluctuations become unconspicuous at high gas and liquid flow rate. In addition, the fluctuation amplitude of relative frictional gradient increases with the increasing of rolling amplitude. However, it is nearly invariable with the rolling period. The traditional correlations which are developed for non-rolling condition give poor predictions for transient frictional gradient when it fluctuates significantly. By taking into account of the influences of rolling parameters, a new correlation applied to calculate the transient frictional resistance in rolling rod bundle is achieved, showing good agreement with experimental results.

1. Introduction

Act as the most key component in any nuclear reactor systems, the reactor core is consisted of many fuel rods bound together which is usually called a rod bundle. The two-phase resistance plays an important role in determining the performance of Boiling Water Reactor (BWR) systems under most operating or transient conditions, and is indispensable for the safety analysis of both BWR and Pressurized Water Reactor (PWR) systems during accident scenarios such as a small break loss of coolant accident or loss of residual heat removal.

Most of the researches concerned on two-phase flow behavior were with the circular tube and rectangular duct, whereas nearly focus on rod bundle. Due to the existence of rod bundles, the flow channel was divided into different types of sub-channels and the two-phase flow characteristics became complex. Narrow et al. [1] studied the two-phase flow patterns and frictional pressure drop in a horizontal micro-rod bundle. They observed six distinct flow patterns including bubbly, slug, froth, stratified-intermittent, annular-intermittent and annular, and found the frictional pressure drops were strongly flow pattern-dependent. Sadatomi et al. [2] carried out air–water two-phase flow distribution in a 2 × 3 rod bundle at ambient pressure and temperature. Their results indicated that the two-phase pressure drop agree well with predictions from a simple, one-dimensional, one-pressure two-fluid model when appropriate equations of wall friction and interfacial friction forces were applied.

The recent trend of application in ocean environment has attracted growing interests on two-phase flow under ocean conditions. By reviewing some open literatures on thermo-hydraulic characteristics of ship nuclear reactors under ocean conditions, Ma et al. [3] pointed out that the rolling motion was the most typical movement among ocean conditions and its effect on fluid flow was most complex. Cao et al. [4] investigated the transient frictional resistance of single- and two-phase flow in rolling circular tubes, and indicated that the conventional correlations provided poor predictions of the transient frictional resistance. Combining transient single-phase frictional coefficient correlation with homogeneous flow model, they proposed correlation for calculating two-phase frictional pressure drop of bubbly flow under rolling condition. Luan et al. [5] and Zhang et al. [6] investigated the effects of rolling motion on two-phase flow pattern transition, and found that rolling parameters and channel size affected the flow pattern transitions dramatically. The influences of rolling amplitude, rolling period, flow rate and mass quality on resistance characteristics of two-phase flow in rolling narrow rectangular

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Nomenclature

General symbols

C	parameter in Eq. (11)
C_{ave}	time-averaged value of C_{roll}
C_{amp}	fluctuation amplitude of C_{roll}
C_{roll}	transient parameter under rolling condition
C^*	ratio of C_{roll} to C
C_0	distribution parameter
D	rod diameter (mm)
D_h	hydraulic diameter (mm)
g	gravitational additional (m/s^2)
h	distance between two pressure pores (mm)
j	superficial velocity (m/s)
j_{av}	two-phase averaged superficial velocity, $0.5(j_g + j_l)$ (m/s)
k_i	coefficient in Eq. (14) ($i = 0, 1, 2, 3$)
l	length scale $l = y$ (m)
$L, r, K_0, C_2, C_3, C_4, C_9$	parameter in Chexal–Lellouche correlation
L_0	entrance length (mm)
P	rod pitch (mm)
r_i	coefficient in Eq. (15) ($i = 0, 1, 2, 3, 4$)
Re	Reynolds number
Re_{gl}	gas transition Reynolds number from laminar to transition flow
Re_{gt}	gas transition Reynolds number from transition to turbulent flow
t	time (s)
t_c	phase difference (s)
T	rolling period (s)
T_c	fluctuation period (s)
V_{gj}	drift velocity (m/s)
x	mass quality
X	Martinelli parameter
y	distance between the test section and the rolling shaft (mm)
z_1, z_2	distances between pressure port and the rolling platform (mm)
ΔP_{add}	additional pressure drop (kPa)
ΔP_f	frictional pressure drop (kPa)
ΔP_g	gravitational pressure drop (kPa)
ΔP_t	total pressure drop (kPa)

Greek letters

α	void fraction
β	angular acceleration (rad/s^2)
θ	rolling angle (rad)
ρ	density (kg/m^3)
σ	surface tension (N/m)
ω	angular velocity (rad/s)
$\Delta\rho$	density difference between phases (kg/m^3)

Subscripts

g	gas phase
l	liquid phase
m	the maximum value
tp	two-phase

ducts were studied experimentally by Xing et al. [7] and Jin et al. [8]. Their results indicated that conventional correlations poorly predict the transient frictional resistance when it fluctuates periodically. New correlations with better accuracy for calculating transient frictional resistance were achieved based on separate flow model as well as homogenous flow model. Yan et al. [9] studied experimentally on adiabatic air–water two-phase flow in a 3×3 rolling rod bundle under stagnant condition. The results showed that rolling motion leaded to the time-averaged void fraction and decreasing and the time-averaged gas rising velocity increasing at low gas flow rate. The increase in rolling amplitude or decrease in rolling period make the fluctuation amplitudes of void fraction and gas rising velocity increasing, and the new correlation was developed for transient parameters under rolling condition. Unfortunately, few researches have been published that address the transient frictional resistance in rod bundle under rolling condition. To better understand the influence of rolling motion on two-phase flow resistance, a series of experiments were conducted by using a 3×3 rod bundle test section. The effects of rolling motion on time-averaged and transient frictional resistance were both investigated.

2. Experimental apparatus

Fig. 1 presents the schematic diagram of experimental facility. The entire system consists of a rolling platform, an air–water mixer and a separator, a 3×3 rod bundle test section, a centrifugal water pump, a water tank, compressed air lines and various piping components. The rolling platform, a 2.5 m $\times$ 3.5 m rectangular plane, can rotate with the central shaft. The two-phase mixture was injected into rod bundle through the air–water mixer. Air was supplied by the compressed air tank which was maintained at 0.3 MPa by a pressure regulator. After the air and water mixture flowed upward through the test section, the air was released into the atmosphere through a separator, while the water was drained back to the water tank by return water pipeline. The two-phase mixture was firstly injected into the rod bundle, and then started the rolling platform by using an automatic system to move under certain rolling period and rolling amplitude. After data under all rolling conditions were recorded, the two-phase flow rate was increased to conduct next test condition. In addition, the experiment was conducted under ambient temperature and pressure.

The rolling motion with a certain rolling period and amplitude was controlled by an automatic system as referred in literature of Xing et al. [10]. Consequently, the rolling angle could be expressed as follow

$$\theta(t) = \theta_m \sin(2\pi t/T) \tag{1}$$

It should be noted that the rolling angle θ represents the angle between the rod bundle and vertical position. Accordingly, the angular velocity ω and the angular acceleration β of rolling platform can be derived by differentiating Eq. (1) once and twice, respectively.

$$\omega(t) = (2\pi\theta_m/T) \cdot \cos(2\pi t/T) \tag{2}$$

$$\beta(t) = (-4\pi^2\theta_m/T^2) \sin(2\pi t/T) \tag{3}$$

where θ_m and T denote rolling amplitude and rolling period, respectively. To evaluate the influences of rolling parameters on two-phase frictional resistance in rod bundle, five following conditions of rolling motion were investigated: $\theta_m 5°T8$ s; $\theta_m 10°T8$ s; $\theta_m 15°T8$ s; $\theta_m 15°T12$ s; $\theta_m 15°T16$ s.

The design dimensions of 3×3 rod bundle test section are presented in Fig. 2. The casing of the rod bundle test section was made of transparent acrylic plates assembled as a 32×32 mm rectangular duct. A total of 9 (3×3) acrylic rods with the diameter of 8 mm