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Flow fluctuations and flow friction characteristics of vertical narrow rectangular channel under rolling motion conditions

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A B S T R A C T

Experimental investigations on flow fluctuations and friction characteristics of a vertical narrow rectangular channel under rolling motion condition are carried out. This experiment is designed to acquire the flow rate fluctuation boundary of forced single-phase flow in rolling motion and to get an insight into the flow friction characteristics under large flow rate fluctuation amplitudes. The results show that the amplitude of flow rate fluctuations increase with increasing rolling amplitude and the valve opening while decrease with the increase of the rolling period and driving head. The time average friction coefficient can be obtained by two kinds of methods, one calculated by integrating the instantaneous friction coefficient in one period is related to the viscous dissipation and the other acquired by the Darcy equation which employs time average pressure drop and velocity represents time average frictional pressure drop. A correlation for the instantaneous friction coefficient is developed, which could also apply to steady condition when the rolling frequency or rolling amplitude approaches zero.

1. Introduction

The marine ship reactor always experiences the effects of ship motions due to sea condition [1,2]. These effects of ship motions such as rolling, heaving and pitching should be taken into account when evaluating the thermal and hydraulic performance of the marine reactor systems. The inclining changes the position of the reactor, while the heaving motion only produces a vertical inertial acceleration. However, the rolling motion not only changes the position of the reactor but also introduces three additional accelerations, which are different in amplitude, direction and frequency, and their effects are different in different system compositions as well. Therefore, the studies of the effect of rolling motion on the thermal hydraulics of marine reactor have received growing attentions in recent years.

Ishida et al. [2], Murata et al. [3,4], Tan et al. [5], Huang et al. [6] studied the flow and heat transfer characteristics in natural circulation flow under rolling motion conditions experimentally. The results of their experiments show that flow rate fluctuates periodically owing to the additional inertial accelerations induced by the rolling motion. Mathematical models were also developed in the study of Murata et al. [3,4] and Tan et al. [5] to calculate flow rate fluctuations of the core and single loop under rolling motion condition, satisfactory agreement between the experiment and calculation was obtained. Similar results can also be found in theoretical works conducted by Yan and Yu [7,8]. Their theoretical studies also found that the flow rate of natural circulation fluctuates with a period equals to the rolling period.

The flow rate fluctuations are confirmed in single-phase natural circulation flow in rolling motion. However, experimental studies of forced circulation flow conducted by Zhang et al. [9], Xing et al. [10] show that flow rate does not fluctuate at all or with a very small amplitude if it does. In the study of Zhang et al. [9], the flow rate does not fluctuate and the flow could be treated as steady. However, the experiment of Xing et al. [10] found that rolling motion renders the flow to fluctuate with relatively small amplitude. Xing et al. [10] believes that when the additional inertial pressure drops are comparable to the driving pressure head and total flow resistance, the fluctuation amplitude of flow rate can be much higher even in a forced circulation flow. However, no elaborate experimental results and in-deep theoretical studies were given in Xing's work. Therefore, more experimental and theoretical work needs to be done to clarify the fluctuation characteristics of flow rate in forced circulation flow.

The fluid dynamics for flow through narrow rectangular channels have been receiving great attention over the last few decades because of their abroad practical applications in the fields such as coolant channels in power and research reactors, high performance micro-electronic device, compact heat exchangers and other heat

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Nomenclature

General symbols

T	rolling period (s)
t	time (s)
u	velocity
S	the surface of a fluid element (m^2)
r	distance of fluid element to rolling axis (m)
f	mass force per kilogram (N/kg)
a_0	translational acceleration (m/s^2)
a_n	centrifugal acceleration (m/s^2)
a_t	tangential acceleration (m/s^2)
a_c	Coriolis acceleration (m/s^2)
l	length between the pressure taps (m)
h_{23}	length of small loop (m)
h_{34}	height of small loop (m)
A	cross section (m^2)
Δp_d	driving pressure head (Pa)
Δp_{add}	additional pressure drop (Pa)
Δp_f	frictional pressure drop (Pa)
Δp_{HL}	measured pressure drop (Pa)
p_{pump}	driving pressure head of pump (Pa)
k	local friction coefficient
D_e	hydraulic diameter of the test section (m)
ΔH	height of rolling loop (m)
ΔL	length of rolling loop (m)
D	driving force term defined in Eq. (18) (m/s^2)
B	amplitude of additional force term defined in Eq. (18) (m/s^2)
C	loop friction coefficient term defined in Eq. (18) (m^{-1})
Q_{amp}	flow rate fluctuation amplitude
Q_{ampr}	relative flow rate fluctuation amplitude
Ga	dimensionless additional force number
Re_{ta}	time average Reynolds number

Greeks

θ	instantaneous rolling amplitude (rad)
ω	angular velocity (rad/s)
β	angular acceleration (rad/s^2)
τ	fluid element
ρ	water density (kg/m^3)
ν	kinematic viscous (m^2/s)
λ	Darcy friction coefficient
μ	dynamic viscous (Pa s)
α	aspect ratio of height to width, less than 1

subscripts

max	the maximum value
m	cross average
d	driving force
ta	time average
f	friction-related
$roll$	rolling condition

superscripts

$'$	relative coordinate

transfer devices. These research results can be found in the studies of Mishima et al. [11], Warrier et al. [12], Ma et al. [13], Wang et al. [14] and Yan et al. [15,16]. However, most studies were carried out in steady state whereas only a few was found in rolling conditions, such as Xing et al. [10] and Yan et al. [15,16]. In addition, the study of Zhao et al. [17] for pulsating flow showed that the flow friction is closely related to the amplitude of flow rate fluctuation in the pulsating flow. Therefore, the flow rate fluctuations in forced circulation flow will be clarified at first in our work, and then the boundary of the flow rate fluctuations is obtained. By employing a narrow rectangular channel and producing large amplitude of flow rate fluctuations intentionally, a series of experiments were conducted to investigate the time average and instantaneous flow friction characteristics of narrow rectangular channel under rolling motion conditions.

2. Experimental setup

The schematic diagram of the experimental setup employed in our experiment is shown in Fig. 1. The experimental setup is composed of rolling platform, flow loop and instrumentation system. Detailed introduction of these three parts will be given in the following sections.

2.1. The rolling platform

The rolling platform which is a 2 m × 2.5 m rectangular plane with a horizontal axis as its rolling axis is shown in Fig. 1. The locked key is used to keep test section vertical. The rolling platform is driven by a crank and rocker mechanism, which is the same as that used by Tan et al. [18]. Different rolling amplitudes can be acquired by changing the length of the rocker and the linkage. A frequency transducer is employed to adjust the frequency of the electromotor and thus changes the rolling period. The motion of a ship at sea can be simulated by the rolling motion that is produced by the rolling platform. The instantaneous rolling amplitude can be approximated by

$$\theta = \theta_{max} \sin(2\pi t/T) \quad (1)$$

Consequently, the rolling angular velocity and angular acceleration are

$$\omega = \theta_{max}(2\pi/T)\cos(2\pi t/T) \quad (2)$$

$$\beta = -\theta_{max}(2\pi/T)^2 \sin(2\pi t/T) \quad (3)$$

where θ_{max} is rolling amplitude, T is rolling period, and t is time.

2.2. The flow loop

The flow loop is schematically illustrated in Fig. 1. Water is circulated from a tank by a centrifugal pump which has a range of flow rates from 0.02 to 3.3 m^3/h. The water which comes out of the pump is divided into two ways. One is pumped to flow through an electromagnetic flow meter, an adjusting valve (valve B) and a rubber tube and enters a narrow rectangular channel. After passing through a symmetric loop composed of a narrow rectangular channel and stainless steel pipe, the fluid flows back to the water tank via another rubber tube. The other way is that water flows back to the water tank by a bypass loop in which an adjusting valve (valve A) is installed. All the outlet parts of backwater pipes are immersed in the water and hence the water tank can be considered as a pressurizer with atmosphere pressure. The symmetric loop is fixed on the rolling platform while the others are installed on the ground. The two rubber tubes are placed close to the rolling axis to lessen the effect of rolling motion.