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A theoretical analysis about the mechanism of the effect of rolling motion on single-phase flow resistance in rectangular duct

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ABSTRACT

Marine reactors are received increasing attention recently, because that the coolant flow behaviors of the offshore nuclear power plants are very complicated and important. In this paper, the mechanism of the effect of rolling motion on single-phase laminar flow resistance in rectangular duct is theoretically studied by the way of analyzing the wall shear stress. The results show that the area-averaged oscillatory velocity fluctuates periodically, with its amplitude increasing as the relative pressure gradient increases and the aspect ratio decreases. When the relative pressure gradient is very low, the flow tends to be steady. The shear stress and wall friction tend to steady flow. While for the high relative pressure gradient, the wall shear stress varies periodically, which leads to the periodical fluctuation of frictional pressure drop. A larger relative pressure gradient and a smaller aspect ratio will intensify the effect of rolling motion on the shear stress and wall friction. Despite that the influence of the rolling motion on shear stress and wall friction, the proportion of frictional resistance due to wide sides out of the total is nearly independent of rolling motion. Finally, the periodically frictional pressure drop in rolling motion is calculated by the present model which is validated by experimental data from literature.

1. Introduction

In recent years, there has been a growing application of nuclear power system in marine transportation. One of the biggest differences between water-cooled marine reactors and land-based reactors is that the former is influenced by rolling, pitching and heaving motions (Murata et al., 2002; Pendyala et al., 2008; Tan et al., 2009; Zhang et al., 2011). Ma et al. (2012) reviewed the thermal-hydraulic behavior of the coolant flow subjected to platform motions, and concluded that rolling motion influences coolant flow and heat transfer behaviors in the most complex way. During the rolling motion of a marine reactor, an inertial force imposes on the coolant, resulting in a periodically oscillatory pressure gradient. These periodical pressure gradients render the flows and processes unsteady. The flow fluctuation and pressure gradient oscillation may induce variations of operating performance in barge-mounted equipment. Therefore plenty of investigations on single-phase flow resistance in rolling motion have been performed previously (Cao et al., 2006; Liu et al., 2012; Tan et al., 2013; Wang et al., 2014a, b; Xing et al., 2011, 2013a; Yan et al., 2010a, b; Zhang et al., 2009). However, characteristics of the flow resistance under rolling condition have not been reached a consensus, because of the incompatible experimental conditions.

Cao et al. (2006) and Zhang et al. (2009) experimentally studied the influence of rolling parameters, flow rates and tube sizes on single-phase flow resistance of forced circulation. They believe that the flow rate of forced circulation is nearly invariable even under rolling condition, but the frictional pressure drop fluctuates periodically and deviates dramatically from the traditional correlations. However, experimental result of Liu et al. (2012) indicates that the transient frictional resistance of single-phase flow in narrow rectangular duct under rolling condition is the same as steady flow, if the flow rate does not fluctuate periodically. The authors' numerical simulation shows that the effect of rolling motion on flow field is so weak that the frictional resistance is similar with steady flow.

Studies of Pendyala et al. (2008), Wang et al. (2014b) and Xing et al. (2011) indicated that the inertial force caused by rolling or heaving motions leads to periodical flow fluctuation and oscillation of frictional pressure drop, and the frictional pressure drop could not be calculated by conventional correlations. The amplitude of flow rate and frictional pressure drop largely depends on the

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Nomenclature

General symbols

A	The surface area of the fluid
A_r	Relative pressure gradient
d_e	Hydraulic diameter (m)
F	Friction resistance along flow direction
g	Gravity acceleration (m/s^2)
h	Height of the duct (m)
l	Characteristic length of the system
L	Length of the duct (m)
M	Parameter, Eq. (10)
P	Pressure acting on the fluid surface (Pa)
P_0	Constant pressure gradient (kPa/m)
r	Distance between fluid and rolling shaft (m)
S	Area of the cross section (m^2)
T	Rolling period (s)
t	Time (s)
t_f	Liquid temperature (°C)
u	Velocities (m/s)
$\bar{u}$	Area-averaged velocity (m/s)
V	The volume of the fluid
w	Width of the duct (m)

Greek letters

α	The aspect ratio, $\alpha = h/w$
β	Angular acceleration (rad/s^2)
Δp_f	Oscillatory pressure drop (kPa)
θ	Rolling angle (°)
θ_m	Rolling amplitude (°)
μ	Dynamic viscosity
ρ	Fluid density
τ	Shear stress
υ	Kinetic viscosity
ω	Rolling velocity (rad/s)
ω_0	Angular frequency of rolling motions (s^{-1})

Superscript

w	Wide side
n	Narrow side
$*$	Dimensionless parameters

Subscript

0	Steady flow
t	Oscillatory flow driven by rolling motion only

magnitude of the inertial force. In recent studies of Tan et al. (2013), Wang et al. (2014a) and Xing et al. (2013a), flow fluctuation behaviors of force circulation are greatly influenced by the pressure head. When the pressure head is relative low, the flow rate fluctuates periodically, however it is nearly invariable for relative high pressure head. Xing et al. (2013a) revealed the mechanism of the effect of rolling motion on single-phase forced circulation with different pump head experimentally. The results show that effect of rolling motion on single-phase flow resistance wears off as the pump head increases. When the pump head is high enough, the velocity and frictional resistance in rolling motion is similar with steady flow. A theoretical correlation is also proposed to calculate the friction factor with arbitrary aspect ratio for the case that the pump head outclasses the additional pressure drop. However, the mechanism of effects of rolling motion with relative low pump head has not been discussed detailedly and systematically, which will be treated by analyzing the wall shear stress in present study.

Rectangular duct is one of preferential choices as a coolant flow channel in compact heat exchangers due to its higher heat transfer efficiency. Therefore researches on coolant flow resistance in rectangular ducts have been received increasing attention over the last few decades (Ma et al., 2011; Xing et al., 2013b). However, most previous work for rectangular ducts was performed under steady condition, only a few can be found in rolling motion (Liu et al., 2012; Tan et al., 2013; Xing et al., 2013a; Yan et al., 2010a,b). The previous experiments mainly focus on macroscopic parameters such as area-averaged flow rate and pressure drop. Therefore the local flow behaviors in rolling motion and the related influence mechanism are unclear. Yan et al. (2010a) gave the single-phase velocity field in rectangular duct under rolling condition, however, the authors has not derived the shear stress and wall friction. Xing et al. (2013a) revealed the mechanism of the effect of rolling motion on single-phase flow resistance theoretically and experimentally, however, the previously work only considered the condition of constant flow rate under rolling conditions. By far, characteristics of wall shear stress and frictional resistance of different sides have not been compared and mechanisms of influences of rolling motion have not been revealed systematically for the condition of oscillatory flow. The influences of relative pressure gradient due to rolling motions on shear stress and wall friction with arbitrary aspect ratio have not been discussed. Additionally, the previously work has not paid enough attention to validate the theoretical models. To better understand the mechanism of effect of rolling motion on single-phase flow resistance, transient shear stress and frictional resistance were studied theoretically. Finally, a theoretical model predicted transiently frictional pressure drop in rolling motion will be proposed.

2. Theoretical model of the wall friction

Tan et al. (2009) and Wang et al. (2014a) performed the force analysis of fluid flow under rolling conditions, and gave the momentum conservation equation:

$$\iiint_V \rho \frac{\partial u}{\partial t} dV = \iiint_V \rho \left[\vec{g} - \vec{\omega} \times \left(\vec{\omega} \times \vec{r} \right) - \vec{\beta} \times \vec{r} - 2\vec{\omega} \times \vec{u} \right] dV + \oint_A \vec{P}\, dA \tag{1}$$

In which, ρ is the fluid density, kg/m^3; g is the gravity acceleration, m/s^2; A and V denote the surface area and the volume of the fluid, respectively. u is the fluid velocity, m/s; r is the distance between fluid and rolling shaft, m; P is the pressure acting on the surface of fluid, Pa. ω and β denote the rolling velocity and acceleration respectively, which can be written as:

$$\omega = -\frac{2\pi\theta_m}{T}\sin(\omega_0 t) \tag{2}$$

$$\beta = -\frac{4\pi^2\theta_m}{T^2}\cos(\omega_0 t) \tag{3}$$

Accordingly, the rolling motion of a ship is simulated by trigonometric function, and the rolling angle can be written as:

$$\theta = \theta_m \cos(\omega_0 t) \tag{4}$$