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Effect of rolling motion on single-phase laminar flow resistance of forced circulation with different pump head

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ABSTRACT

Effects of rolling motion on single-phase laminar flow resistance during forced circulation with different pump heads were investigated. Purified water was used as the working fluid and the flow rate ranged from 0.04 to 0.16 m^3/h. Different pump heads were obtained by a variable speed electromotor, by which the flow rate was controlled combining with a regulating valve. The experimental results indicate that the influence of rolling motion on transient flow rate and frictional resistance largely depends on the pump head. The flow rate in rolling motion oscillates periodically with its amplitude decreasing rapidly as the pump head increases, and finally, tends to be steady as the pump head further increases to a high level. The system flow resistance curve and pump performance curve are employed to analyze the characteristics of flow oscillation. When the pump supplies a low head, the frictional pressure drop fluctuates asynchronously with the flow rate and could not be predicted by conventional correlations. While the pump supplies a high head, the frictional pressure drop does not fluctuate and could be predicted by conventional correlations. Effects of rolling motion on single-phase laminar flow resistance are clarified by analyzing the velocity distribution. In spite of the above mentioned effects, rolling motion has no influence on time-averaged flow resistance regardless of the pump head.

1. Introduction

In recent years, with the extensive application of nuclear power system in marine transportation, effects of ocean conditions (rolling, pitching, heaving, etc.) on coolant flow in these systems have attracted increasing attention. For a marine reactor, the rolling induced inertial force is imposed on the primary coolant, about which a number of investigations have been performed previously (Cao et al., 2006, 2007; Gao et al., 1997; Ishida and Yoritsune, 2002; Isshiki, 1966; Murata et al., 2002; Pang et al., 1995; Tan et al., 2009a,b,c; Xing et al., 2012; Yan et al., 2010a,b; Zhang et al., 2009).

Gao et al. (1997), Tan et al. (2009a) and Yan and Yu (2009) performed theoretical investigations on single-phase flow behaviors in rolling motion using of one-dimension momentum conservation equation. Their results indicated that the flow rate of a natural circulation loop will oscillate sinusoidally, whereas almost keeps constant for a forced circulation loop. Recently, Yan et al. (2010a,b) proved that rolling movement only influences the velocity distribution near the tube wall, while does not influence mean frictional resistance. However, the previous theoretical studies didn't consider the effect of pump head on flow resistance.

Because of the complexity of flow and heat transfer behaviors in rolling motion, most previous studies were performed experimentally. Tan et al. (2009a,b,c) conducted experiments to investigate effects of rolling period, rolling amplitude, flow rate and the component layout of the experimental loop on thermal hydraulic behavior of a natural circulation loop. The results show that rolling motion makes the flow fluctuate easily, impairs the natural circulation capacity, whereas enhances the heat transfer. Cao et al. (2006, 2007) and Zhang et al. (2009) experimentally investigate the effect of rolling parameters, flow rate and tube size on single-phase flow resistance in a circular tube. In their studies, the flow rate is nearly invariable, but the frictional pressure drop fluctuates periodically. They also pointed out that the experimental results under rolling condition deviates dramatically from the traditional correlations. Studies of Pendyala et al. (2008) indicated that periodical additional force caused by heaving movement makes single-phase forced flow fluctuation, and the mean friction factor is greater than that in steady conditions. Ishida and Yoritsune (2002), Murata et al. (2002) and Tan et al. (2009a,b) studied the characteristic of single-phase natural circulation in rolling motion, affirming the influence of rolling movements on flow and heat transfer behaviors. From afore-mentioned work, it is explicit that the fluid flow in an oscillating pipe is rather different from that in a pipe at rest, whereas, few relevant study deals with the effect of pump head on flow resistance. In recent studies of Xing et al. (2012) and Wang et al. (2012c), the fluctuation amplitude of the flow rate decreases rapidly as the pump head increases. However, the mechanism of effect of rolling motion on

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Nomenclature

General symbols

f	rolling frequency (Hz)
T	rolling period (s)
t	time (s)
θ_m	rolling amplitude (rad)
ΔP_t	measured pressure drop (kPa)
ΔP_f	frictional pressure drop (kPa)
ΔP_a	additional pressure drop (kPa)
ΔP_{as}	total additional pressure drop of the pressure pipes and the test section (kPa)
ΔP_{sum}	the total flow resistance (kPa)
PH	pump head (m)
H	height of the experimental loop, Fig. 1 (m)
L	width of the experimental loop, Fig. 1 (m)
h	height of the pressure drop measurement system, Fig. 1 (m)
l	length of the pressure drop measurement system, Fig. 1 (m)
F_i	the overall flow resistance including additional pressure drop, Eq. (12)
d_e	hydraulic diameter (m)
g	gravity acceleration (m/s^2)
Q	volumetric flow rate (m^3/h)
ΔQ	fluctuation amplitude of flow rate (m^3/h)
b	amplitude of additional pressure drop (Pa), Eq. (9)
x', y', z'	relative coordinates fixed on rolling platform
Re	Reynolds number ($Re = \rho\overline{u}d_e/\mu$)
$\bar{u}$	area-averaged velocity (m/s)
u	velocity in cross section (m/s)
f_t	inertia force per unit mass (N/kg)
dp/dz	pressure gradient along flow direction (Pa/m)
n	rotation speed of the pump (r/min)

Greek letters

θ	rolling angle (rad)
ω	angular velocity (rad/s)
β	angular acceleration (rad/s^2)
ρ	water density (kg/m^3)
α	the ratio of the duct height to width
λ	friction factor
τ	viscous stress (N/m^2)
μ	dynamic viscosity (Pa.s)

Subscripts

1, 2	start and end points
i	parameters for the pump head *i*
av	averaged
max	maximum
min	minimum
roll	parameters in rolling motion
c	rated parameters

single-phase forced flow resistance with different pump head has not been compared carefully so far.

Rectangular duct is one of the choices as the heat transfer tube in a compact heat exchanger due to its higher heat transfer efficiency and less space requirement. Therefore, researches on thermal hydraulic behaviors of coolant flow in rectangular ducts have received increasing attention over the last few decades (Ma et al., 2011; Shah and London, 1978; Wang et al., 2012a,b; Xing et al., 2011). Most previous work in terms of flow resistance in rectangular duct was performed under steady condition, few can be found in rolling motion. To better understand the mechanism of effect of rolling motion on single-phase forced flow resistance with different pump head, characteristics of flow rate and frictional pressure drop in a rolling rectangular duct (2 mm × 40 mm × 1100 mm) were studied detailedly.

2. Experimental apparatus

2.1. Rolling platform

The rolling platform, a 2.5 m × 2 m rectangular plane, can rotate with its central shaft (*O–O*) as shown in Fig. 1. It is driven by a crank and rocker mechanism as introduced previously by Tan et al. (2009a,b,c) and Zhang et al. (2009). Consequently, the rolling angle can be expressed as follows:

$$\theta = \theta_m \sin(2\pi ft) \tag{1}$$

The rolling movement starts in counter-clockwise direction as shown in Fig. 1. Accordingly, the angular velocity and angular acceleration of rolling platform are deduced as follows:

$$\omega = 2\pi f\theta_m \cos(2\pi ft) \tag{2}$$

$$\beta = -4\pi^2 f^2\theta_m \sin(2\pi ft) \tag{3}$$

where f, T and θ_m denote rolling frequency, rolling period ($f = 1/T$) and rolling amplitude, respectively. The ranges of rolling parameters are rolling amplitude of 10°, 15° and 20°, rolling period of 10 s, 15 s and 20 s.

2.2. Experimental loop and instruments

The schematic diagram of the experimental loop is also shown in Fig. 1. It consists of a pump, a condenser, a test section and a pre-heater. Purified water is used as the working fluid. The pump is driven by a variable speed electromotor whose rotation speed is controlled by the frequency controller. Therefore different pump head is obtained easily by changing the input frequency. According to the principle of similarity, the pump head is proportional to the rotation speed of the pump ($PH_i/PH_c = n_i^2/n_c^2$, n is the rotation speed of the pump, r/min). The rated pump head (PH_c) and the corresponding rotation speed (n_c) are 64 m and 2980 r/min respectively. Therefore the pump head used in the experiments can be calculated by the above correlation as listed in Table 1.

The test section with the size of 2 mm × 40 mm × 1100 mm is made of plexiglas, and mounted vertically on the rolling platform. The height is measured by clearance gauge with an error of ±0.02 mm. The two pressure taps, located along the center line of one larger plane as shown in Fig. 1, are spaced 0.7 m apart and the lower one (p_1) is 0.175 m away from the inlet. The narrow side and wide side of the cross section are perpendicular and parallel to the rolling shaft respectively as shown in Fig. 1.

Three fundamental parameters are required for the data processing, which are the flow rate, pressure drop and the water temperature. The electromagnetic flow meter (H1014376) has an overall uncertainty of ±0.5% and a span of 0–3 m^3/h. Differential pressure transducer (CECCS43: 0–10 kPa) has an uncertainty of ±0.2%. The temperature measurements are performed at inlet and outlet of the test section with *N*-type thermocouples (the maximum error is ±0.5 °C). All the test signals are recorded by data acquisition system (the sampling frequency is 9 Hz and the uncertainty is ±0.1%).