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# Flow fluctuation behaviors of single-phase forced circulation under rolling conditions

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ABSTRACT

Marine reactors are received increasing attention recently in the field of ocean engineering. The effect of platform motion on the coolant flow of an offshore nuclear power plants is very complicated, which is required further analysis. In this paper, effects of rolling motion on single-phase flow fluctuation with different loops were investigated experimentally. And a mathematical model was also developed to study the mechanism of the influence of rolling motion on flow fluctuation with different pressure head, rolling parameters and layouts of flow loops. For the closed loop, the flow rate was adjusted by two ways, i.e. regulating the pump rotation speed and changing the state of regulating valve. While for the opened loop, the pressure head was always supplied by elevated water tank. The Reynolds number ranged from 300 to 8000, and ranges of the rolling period and amplitude were 8–20 s and 10–30°, respectively. The results show that increase of the loop resistance and pressure head results in smaller flow fluctuation amplitudes. Effects of rolling motion on single-phase flow fluctuation weaken as the oscillatory pressure drop decreases or the pressure head increases. If the pressure head is high enough, the effect of rolling motion on flow fluctuation could be neglected. Rolling motions influence the flow fluctuation behaviors in different ways for the opened loop and the closed loop, due to the inequable oscillatory pressure drop. The flow fluctuation model shows a good agreement with the experiments and the analyzing method is expected to other oscillating flow system.



## 1. Introduction

In recent years, with the extensive application of nuclear power system in marine transportation, effects of ocean conditions (rolling, pitching and heaving motions etc.) on coolant flow in these systems have attracted increasing attention. For a marine reactor, the coolant is under the action of the inertia force induced by the variable winds and dynamic ocean waves. These periodical forces render the flow fluctuation and processes unsteady. The flow fluctuation and pressure drop oscillation may induce the change of operating performance in barge-mounted equipment. Therefore plenty of investigations on flow fluctuation and pressure drop oscillation in rolling motions have been performed previously (Cao et al., 2006; Gao et al., 1997; Gu and Ju, 2012; Ishida and Yoritsune, 2002; Murata et al., 2002; Pang et al., 1995; Pendyala et al., 2008; Tan et al., 2009, 2013; Wang et al., 2012, 2013, 2014a; Xing et al., 2011, 2012, 2013; Yan and Yu, 2009; Yan et al., 2011; Zhang et al., 2009).

Hao et al. (2012), Pang et al. (1995), Tan et al. (2009) and Yan and Yu (2009) have calculated the single-phase flow rate in rolling motion by using one-dimension momentum conservation equation. Their results indicated that the flow rate for natural circulation oscillates sinusoidally, whereas almost keeps constant for forced circulation. However, these studies did not consider the effect of rolling motion on flow fluctuation with different pressure head and the influence mechanism. As a result of the complexity of flow resistance and heat transfer behaviors in rolling motion, more previous studies were performed experimentally. Ishida and Yoritsune (2002), Murata et al. (2002), Tan et al. (2009, 2013) and Wang et al. (2012, 2013, 2014a) studied characteristics of flow fluctuation, frictional pressure drop and heat transfer of single-phase pulsating flow induced by rolling motion, affirming the influence of periodical oscillation flow. 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. However, the flow fluctuation behaviors of forced circulation under ocean conditions (mainly refers to rolling, pitching and heaving motions) have not been reached a consensus, because of the incompatible experimental conditions.

In studies of Cao et al. (2006), Liu et al. (2012) and Zhang et al. (2009), the flow rate of single-phase forced circulation is nearly

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**Nomenclature**

| | |
|---|---|
| $\theta'$ | rolling angle (rad) |
| $\theta_m$ | rolling amplitude (°) |
| $\theta'_m$ | rolling amplitude (rad) |
| $\omega_0$ | angular frequency of oscillation, Eq. (4), ($s^{-1}$) |
| $\omega$ | angular velocity (rad/s) |
| $T$ | rolling period (s) |
| $t$ | time (s) |
| $\beta$ | angular acceleration (rad/$s^2$) |
| $l_j$ | length of control volume $j$ |
| $A_j$ | sectional area of control volume $j$ |
| $W$ | mass flow rate (kg/h) |
| $\Delta p_{dr}$ | the pressure head (kPa) |
| $\Delta p_{osc}$ | the oscillatory pressure drop (kPa) |
| $\Delta p_{a,m}$ | the amplitude of additional pressure drop, Eq. (8), (kPa) |
| $\Delta p_{re}$ | the total flow resistance of the loop (kPa) |
| $\Delta p_{cl}$ | pump head or the pressure head of water tank |
| $\Delta p_a$ | the total additional pressure dorp (kPa) |
| $\Delta p_g(t)$ | the total gravitational pressure drop (kPa) |
| $\Delta W$ | amplitude of the mass flow rate (kg/h) |
| $g$ | gravity acceleration (m/$s^2$) |
| $\rho$ | water density (kg/$m^3$) |
| $H$ | height of the experimental loop, Fig. 1 (m) |
| $L$ | width of the experimental loop, Fig. 1 (m) |
| $Re$ | Reynolds number |
| $\zeta$ | the modified resistance factor |
| $W_{rel}$ | the relative flow rate |
| $F$ | the flow resistance in rolling motion, Eq. (18) |
| $m_0$ | the total resistance coefficient for steady flow |
| $m_r$ | flow resistance coefficient of the entire loop under rolling condition |

invariable. The test sections include circular tube and rectangular duct, covering both the vertical and horizontal flow directions, and the experimental loops contain the opened loop and closed loop. They experimentally investigated the effect of rolling parameters, average flow rates and tube sizes on flow resistance. Their results indicate that the frictional pressure drop under rolling condition deviates dramatically from the traditional correlations with the exception of Liu et al. (2012). However, studies of Liu (2008), Pendyala et al. (2008), Wang et al. (2013, 2014a) and Xing et al. (2011, 2012) indicated that periodical force caused by rolling or heaving motions leads to flow fluctuation and pressure drop oscillation even for single-phase forced circulation, and the frictional pressure drop could not be predicted by the conventional correlations. The flow fluctuation amplitude largely depends on the magnitude of the periodical force. In recent studies of Xing et al. (2012, 2013), Tan et al. (2013) and Wang et al. (2012, 2014b), influence of rolling motion on flow fluctuation weakens greatly as the pressure head increases. The flow rate fluctuates periodically under the condition of relative low pressure head, whereas, it is nearly invariable for relative high pressure head.

However, the previous work of Tan et al. (2013), Wang et al. (2012, 2014b) and Xing et al. (2013) mainly dedicate to discussing the flow fluctuation behaviors of the closed loop, of which the oscillatory pressure drop and flow fluctuation behaviors are quite different from the opened loop. The mechanism of effects of rolling motion on single-phase flow fluctuation with different experimental loops needs to be compared systematically. Moreover the threshold pressure head over which the effect of rolling motion on flow fluctuation could be neglected has not been discussed in detail, especially for the opened loop. To the authors' knowledge, few previous attentions were paid to compare the adjusted ways of regulating the pump head and the valve, which is significant importance to reveal the mechanism of the influence of rolling motion on flow fluctuation. The main purpose of this paper is to compare the influence of rolling motion on flow fluctuation for different flow loops, and discuss the critical pressure head over which the influence of rolling motion on flow fluctuation of single-phase forced circulation could be neglected.

## 2. Experimental apparatus

The rolling movement of a ship was simulated by a simple harmonic motion with the help of rolling platforms (Tan et al., 2009; Wang et al., 2013; Xing et al., 2012). Consequently, the rolling angle, angular velocity and angular acceleration could be expressed as follow, respectively:

$$\theta' = \theta'_m \sin(\omega_0 t) \quad (1)$$

$$\omega = d\theta'/dt = \theta'_m \omega_0 \cos(\omega_0 t) \quad (2)$$

$$\beta = d\omega/dt = -\theta'_m \omega_0^2 \sin(\omega_0 t) \quad (3)$$

$$\omega_0 = 2\pi/T \quad (4)$$

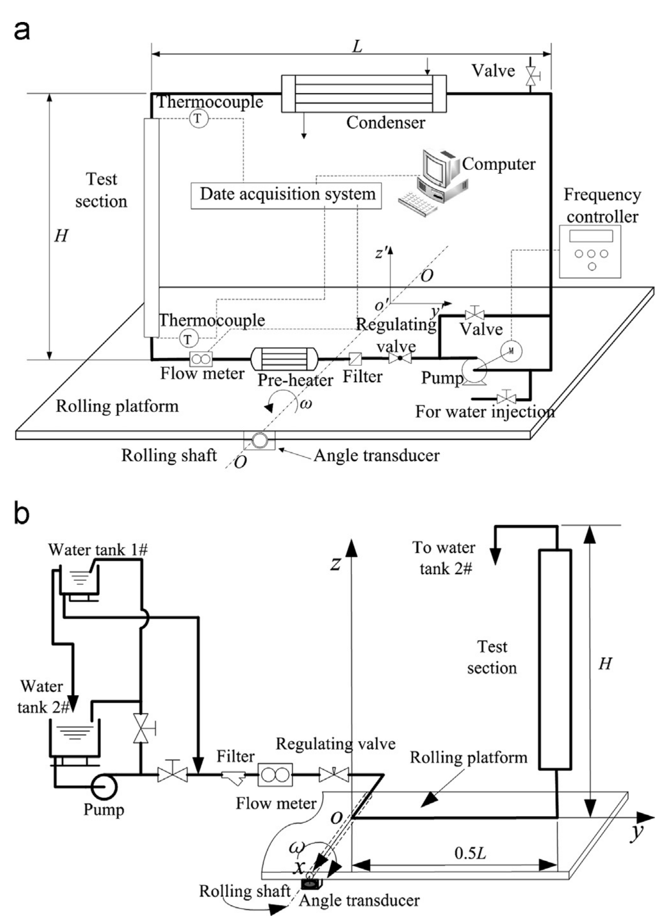


**Fig. 1.** Schematic diagram of the experimental loops: (a) the closed loop; and (b) the opened loop.