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Investigation of flow pulsation characteristic in single-phase forced circulation under rolling motion

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ABSTRACT

The effect of additional inertial forces on the flow rate pulsation in rolling motion condition is theoretically and experimentally studied, and the essential influencing factors that affect the flow pulsation behavior are clarified. Both the theoretical and experimental results indicate that the relative pulsation amplitude of flow rate increases with the driving head increasing, however, it decreases with the increase of experimental loop friction resistance. Furthermore, the investigation results also indicate that the effect of additional inertial force can be neglected and the flow rate will not present significant pulsation when the intensity of driving force is 10 times larger than the additional inertial force. The pulsation intensity of flow rate in rolling motion condition depends on the relative quantity of driving head, friction resistance and additional inertial acceleration.

1. Introduction

Marine-type reactor differs from the land-based reactor. As the complex sea makes the ship move with the ocean waves, for this reason, the thermal–hydraulic characteristics of the marine-type reactor can be affected by the ship motion. As shown in Fig. 1, the typical ship's motion can be generally decomposed into 6 degrees of freedom of movement, which is yawing, pitching, rolling, surging, heaving and swaying.

Recently, several investigators (Ishida et al., 1990; Ishida and Yoritsune, 2002; Murata et al., 1990, 2000, 2002; Pendyala et al., 2008a,b; Guo et al., 2008; Tan et al., 2009a,b; Zhang et al., 2009; Yan et al., 2010a,b,c; Wei et al., 2011) conducted a series of studies on the effect of ship motion on the thermal–hydraulics of the marine reactor under both the forced and natural circulation condition.

Murata et al. (1990, 2000) carried out a series of sing-phase natural circulation experiments in a dual-loop circulation simulating marine reactor to study the effect of the rolling motion on the heat transfer in the core. The results show that the loop flow rate in each leg changes periodically with the rolling motion due to the inertial force of the rolling motion, but the core flow rate does not fluctuate significantly. Furthermore, the heat transfer in the core is enhanced due to the internal flow caused by the rolling motion. Ishida et al. (1990) investigated the effect of sea wave on the thermal hydraulics of the marine reactor system based on the experiments of the first Japanese nuclear ship 'Mutsu'. They found the water level in steam generators and pressurizer can be easily affected by ship motion, the free surfaces and the detecting system will be affected by accelerations and inclinations of the ship caused by the external factors. Gao et al. (1997) proposed a mathematical model of primary coolant and provides a basis for the study of thermal–hydraulics characteristics under ship motion condition. The comparison of heaving upon the forced circulation and natural circulation were conducted and the results show that heaving has less effect upon the primary loop's coolant flow rate and PWR outlet power in case of forced circulation but strongly influenced the natural circulation ability.

Pendyala et al. (2008a,b) experimentally studied the single-phase flow and heat transfer characteristics under heaving motion condition. The results showed that the periodic flow rate pulsation aroused by the heaving motion evidently influences the friction and heat transfer coefficients, in addition, they found that the relative amplitude of flow rate fluctuations decreases with the increase of Reynolds number. Tan et al. (2009a,b) experimentally studied the single-phase natural circulation heat transfer under rolling motion condition in a single-loop simulated marine reactor. The experimental results show that the heat transfer is enhanced with the increasing rolling amplitude and frequency, in addition, the inertial force caused by the rolling motion and the variation of the natural circulation driving force due to the change of effective height leads to the flow rate pulsating significantly. Xing et al. (2011a,b, 2012) conducted a series of single-phase flow experiments under rolling motion condition and found rolling motion leads to fierce flow pulsation at a lower flow rate, but the pulsation

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Nomenclature

General symbols

A	cross section area, m^2
a	acceleration, m/s^2
F	force, N
g	gravity acceleration, m/s^2
L	length, m
P	pressure , Pa
r, R	length, m
t	time, s
t_R	rolling period, s
u	velocity, m/s
V	fluid element volume, m^3
x, y, z	coordinates

Greek symbols

ω	angular velocity, rad/s
θ	angle, rad
β	angular acceleration, rad/s^2
ζ	dimensionless friction factor
ρ	density, kg/m^3

Subscripts

ce	centripetal acceleration
co	Coriolis acceleration
d	driving head
eff	effective value
f	friction resistance
m	maximum value
ta	tangential acceleration

Superscripts

$*$	dimensionless value
$'$	rolling condition

diminished gradually with the increasing average flow rate. Recently, Du et al. (2011); Du and Zhang (2010) conducted the forced circulation single-phase flow and heat transfer experiments under rolling motion condition, the results show that the flow rate does not change with the rolling motion in both laminar and turbulent flow, and the friction and heat transfer coefficients are the same with that in the static state. In addition, Yan et al. (2010a,b,c) established a series model to predict the effect of ship motion on thermal hydraulic characteristics based on the pulsation flow and found that the flow rate pulsation evidently changed the flow and heat transfer characteristics.

Furthermore, Ishida and Yoritsune (2002); Guo et al. (2008); Tan et al. (2009c) all found the complex overlap effect of flow rate pulsation introduced by the inertial force in rolling motion and the density wave instability which tends to make the system more unstable. More recently, Wei et al. (2011) simulated the bubble behavior under swing condition and found the effect of inertial forces caused by swaying is negligible, but the pulsation of mass flow rate caused by swaying motion influences the forces acting on bubble significantly. Therefore, whether the rolling motion can significantly influence the thermal hydraulics or not lies in the pulsating intensity of flow rate. In addition, as mentioned by Tan et al. (2009a), the heaving, yawing and swaying motion only introduces the inertial force to the fluid system, however, the rolling motion not only introduces the inertial force, but also changes the relative spatial location between heat source and condenser due to the successive changes of inclining angle, so it is important to clarify the rolling motion from others ship motion.

Therefore, it can be concluded that the ship motion affects the marine reactor system in two aspects: one is the inertial force

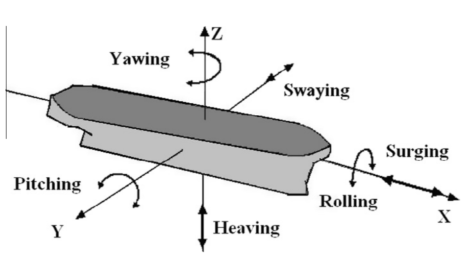

Fig. 1. Types of ship motion.

imparted by the ship motion will impose on the primary coolant likely lead to the flow rate pulsation, the other is the successive variation of inclining angle will change the thermal driving head of the natural circulation loop. In addition, it can be easily understood that the continual variation of inclining angle under ship motion conditions would not affect the driving head in single-phase forced circulation. Therefore the predominant influence factor that may create a significant change of thermal–hydraulics is inertial acceleration in the forced circulation.

From the viewpoint of marine reactor safety, it is important to clarify the essential factor that determines the flow rate pulsation amplitude under rolling motion condition. No previous studies can be found on this subject, although several studies have focused on the effect of rolling motion on the thermal hydraulics in simple reactor systems.

In this paper, the effect of additional inertial forces on the flow rate is theoretically and experimentally studied, and the essential influencing factors that affect the flow pulsation behavior are clarified.

2. Momentum conservation equation

In a general way, the rolling motion of ship movement is simulated as a sinusoidal function (Murata et al., 1990; Tan et al., 2009b), and the rolling angle can be approximated by

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

In which, $\theta(t)$ is the instantaneous rolling amplitude, rad, θ_m is the maximum rolling amplitude, rad, t_R is the rolling period, s, t is the time, s.

Thus, the angular velocity and angular acceleration can be written as

$$\omega(t) = -\theta_m(2\pi/t_R)\cos(2\pi t/t_R) \tag{2}$$

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

In which, $\omega(t)$ is the angular velocity, rad/s, $\beta(t)$ is the angular acceleration, rad/s^2.

The force analysis of the fluid element in an upright pipe under rolling motion condition is shown in Fig. 2, there are three inertial accelerations imposed on the fluid, namely, centripetal acceleration, tangential acceleration, Coriolis acceleration. Accordingly,