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Experimental and numerical study on single-phase flow characteristics of natural circulation system with heated narrow rectangular channel under rolling motion condition

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ABSTRACT

Effects of rolling motion on flow characteristics in a natural circulation system were investigated experimentally and numerically. The numerical results from validated code were mainly used to provide detailed information for the discussion and analysis of experimental results. The results indicate that under rolling motion condition, the phasic difference between flow rate and frictional pressure drop of narrow rectangular channel is negligible. Angular acceleration is the eigenvalue for the effects of rolling motion on flow rate under single-phase natural circulation condition. When angular acceleration is approximately equal, even though either the angle or the period of rolling motion is different, peak, trough and time-averaged values of flow rate are approximately equal. Under rolling motion and single-phase natural circulation conditions, the phenomenon that dimensionless time-averaged mass flow rate is smaller than that under steady state condition is controlled by the nonlinear relationship between mass flow rate and the resistance of loop. The factor also causes the result that the absolute difference of dimensionless flow rate between peak and steady state is smaller than that between trough and steady state. The startup model which is proposed in present paper can be used to predict the flow characteristics of single-phase natural circulation system at startup stage of rolling motion favorably. The self-developed code can simulate instantaneous flow characteristics of single-phase natural circulation system under rolling motion and steady state conditions correctly. The resistance correlations for steady state flow can be directly applied to calculate instantaneous resistance of narrow rectangular channel under rolling motion condition with satisfying agreement with experimental results.

1. Introduction

Natural circulation system, which can improve inherent safety of reactor, simplify structure of system and reduce noise source, has been extensively applied in design of nuclear power plant (Guo et al., 2015; Wang et al., 2014a,b,c; Ruspini et al., 2014; Sarkar et al., 2014; Yan et al., 2009). With the development of nuclear industry, nuclear power plant has also been extensively applied in ocean engineering. Therefore, effects of ocean condition on the performance of natural circulation system have been attracting increasing attention in recent years. Under ocean condition, nuclear power plant may experience very intricate movements which include surging, swaying, heaving, rolling, pitching and yawing. It is noted that rolling and pitching are the most common manners of these six single movements (Yan et al., 2009; Yan and Yu, 2012). Investigations on the effects of ocean condition on natural circulation system have been started early (Isshiki, 1966; Pang et al., 1995; Gao, 1997a,b, 1999; Su et al., 1996; Ishida and Yoritsune, 2002; Kim et al., 2001). Their experimental researches mainly focus on the effect of incline and heaving on natural circulation loop and the effect of ocean condition on critical heat flux. The theoretical researches mainly pay attention to the effect of ocean condition on heat removal ability of natural circulation. Furthermore, the test sections in these researches are circular channel and rod bundles. In past years, most of studies focused on the effects of ocean condition on forced circulation system (Xing et al., 2013a, 2014a; Wang et al., 2013, 2014; Jin et al., 2014; Wang et al., 2014a,b,c; Yan et al., 2015, Tian et al., 2014). Therefore, it has important significance to study the thermo-hydraulic performance of natural circulation system with heated narrow rectangular channel under rolling motion.

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Nomenclature

General symbols

t	time (s)
$\bar{T}$	period of rolling motion
Δp	pressure drop (Pa)
y	y-axis coordinate (m)
z	z-axis coordinate (m)
g	acceleration of gravity (m·s^{-2})
W	mass flow rate (kg·s^{-1})
u	velocity (m·s^{-1})
p	pressure (Pa)
T	temperature (°C)
c_p	specific heat (J kg^{-1} K^{-1})
l	length of flow direction
a	additional inertia acceleration (m·s^{-2})
i	specific enthalpy (J·kg^{-1})
S	source of unit volume (J·m^{-3})
d	equivalent diameter of the tube (m)
Re	Reynolds number
Nu	Nusselt number
Pr	Prandtl number

Greek letters

θ	Rolling angle (rad)
ω	angular velocity (rad·s^{-1})
β	angular acceleration (rad·s^{-2})
ρ	density (kg·m^{-3})
κ	thermal conductivity (W·m^{-1}·K^{-1})
λ	frictional factor
μ	dynamic viscosity (Pa·s)
$\dot{\phi}$	source of unit volume in wall (J·m^{-3})
ξ	local factor

Superscript and Subscripts

i,j	number of control volume
dp	differential pressure
ts	test section
pp	pressure pipe
add	additional
gr	gravitational
roll	rolling motion
fri	frictional
pro	projection of vector
loc	local
f	fluid
w	wall

Vector

$\boldsymbol{a}$	additional inertia acceleration vector
$\boldsymbol{g}$	gravity vector in the non-inertia system
$\boldsymbol{l}$	vector of flow direction
$\boldsymbol{\omega}$	angular velocity vector
$\boldsymbol{\beta}$	angular acceleration vector
$\boldsymbol{r}$	location vector

Among the studies published, studies of Xing et al. (2013a, 2014a), Tan et al. (2013) and Wang et al. (2014a, 2014b, 2014c) indicated that 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. Furthermore, the studies of Tan et al. (2013) and Wang et al. (2014a, 2014b, 2014c) had given the boundary of flow rate fluctuations. The investigations of Ishida and Yoritsune (2002), Murata et al. (1990), Murata et al. (2000), Murata et al. (2002) and Tan et al. (2009a, 2009b, 2009c) reveals that the rolling motion causes the natural circulation flow rate pulsating remarkably. Wang et al. (2014a, 2014b, 2014c) pointed out that the smaller driving head of natural circulation than that of forced circulation is the main cause for the phenomena. Compared with two-phase natural circulation and forced circulation with low pump head, under stable flow condition, single-phase natural circulation has a relative smaller driving force. Therefore, it would then cause more remarkable flow fluctuation under rolling motion condition. Meanwhile, in the engineering application point of view, the single-phase flow of natural circulation is very important. Hence, it is necessary to study the effect of rolling motion on single-phase flow of natural circulation in ocean engineering.

Studies of Tan et al. (2009a) pointed out that the average mass flow rate of natural circulation decreases with increase in rolling amplitude and frequency, however, the mechanism of such effect is not presented. Meanwhile, due to the complexity of unsteady state, most of experimental studies on the effects of rolling motion are focused on time-averaged flow characteristics (Xing et al., 2013a, 2014a; Wang et al., 2014a,b,c; Tan et al., 2009a) under flow fluctuation condition. In studies of Yan et al. (2009, 2012), a thermal hydraulic code in rolling motion condition is developed on the basis of RELAP5/MOD3.3 code by adding a module to consider the effect of rolling motion and introducing new flow and heat transfer models. To sum up, very little work has been carried out to research the mechanism of the effect of rolling motion on instantaneous flow characteristics of single-phase natural circulation, especially the startup stage of rolling motion.

In present paper, instantaneous and time-averaged flow characteristics are studied both experimentally and numerically. Furthermore, the flow characteristics in startup stage of rolling motion are also studied. Meanwhile, the mechanism of effect of rolling motion on flow characteristic is interpreted. Finally, the empirical model of startup stage is given and validated. The result may provide a basis for the design of a natural circulation system of floating nuclear power plant at sea.

2. Experimental apparatus and parameters

2.1. Experimental facility

Schematic diagram of the experimental facility is shown in Fig. 1. The experimental facility is composed of a primary circulation loop, a secondary circulation loop, a rolling motion driving mechanism and a data acquisition system. Through the heat exchange in cooling tower, atmosphere environment serves as ultimate heat sink of primary circulation loop.

The primary loop consists of a test section, a preheater, pressurizer, a self-priming pump, primary side of condenser, valves and connecting pipes. They are mounted on the rolling platform. Therefore, the loop can be rolled periodically around the axis of the platform. Purified water is used as the working fluid and all the experiments are performed in single-phase flow. During startup stage in experiments, working fluid was driven by the pump and flowed upward through the test section. The secondary loop is composed of a filter, a secondary pump, secondary side of condenser, a cooling tower, a fan, a water tank, valves and connecting pipes. The secondary side of condenser is connected to other part of secondary loop with flexible pipe. The rolling platform, a