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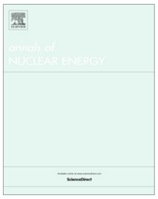

Experimental and numerical study on fluctuations and distributions of fluid temperature under rolling motion conditions

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ABSTRACT

An experimental and numerical study is conducted on a narrow rectangular channel of a loop under natural circulation conditions with rolling motion to investigate temperature fluctuations and mechanisms that influence such fluctuations. Meanwhile, the temperature distribution along the channel under rolling motion conditions is predicted based on a self-developed code. The results show that the cycle-averaged liquid temperature at the outlet of the test section under rolling motion conditions is higher than that under vertical conditions. The waveform of fluctuations in fluid temperature is complex and deviates from the standard sine curve, which is the law of the rolling platform. In the single-phase natural circulation loop, temperature fluctuations at the outlet of the test section are spurred from flow rate fluctuations caused by rolling motion in a dominant manner. Instantaneous temperature fluctuations are successfully predicted from the self-developed code for the single-phase natural circulation loop of a heated narrow rectangular channel under rolling motion conditions. Under rolling motion and constant heat flux conditions, the amplitude of temperature fluctuations in the heated zone increases along the flow direction. Along the flow direction, phases of the temperature crest at different locations of the heated zone exhibit a lag effect. In the adiabatic section between the outlets of the heated zone and test section, the amplitude of temperature fluctuations decreases, and the waveform is smoothed along the flow direction. Moreover, the instantaneous temperature distribution in the heated zone is approximately linear along the flow direction when the flow rate remains positive during rolling motion.

1. Introduction

With the development of the nuclear industry, nuclear power plants have been extensively applied in ocean engineering (e.g., floating nuclear power plants and nuclear-power icebreakers). Therefore, the effects of ocean conditions (e.g., rolling, heaving, pitching, and inclination) on thermal hydraulic characteristics have attracted interest in recent years. As a typical ocean condition, rolling motion conditions have attracted more attention than other conditions. In recent decades, a number of investigations have been conducted on the effects of rolling motion on characteristics of single-phase heat transfer (Wang et al. (2013), Chang et al. (2008), Murata et al. (2000), Tan et al. (2009a), Yan et al. (2010a, b)) and flow resistance (Xing et al., 2013a,b; Yan et al., 2010c,d; Yan and Gu, 2011; Tan et al., 2013; Yan et al., 2014; Yuan et al., 2016). Investigations have reported on system behaviors experimentally, theoretically and numerically (Murata et al. (2002), Tan et al. (2009b), Wang et al. (2014), Yan and Yu (2012), Yu et al. (2015)).

Wang et al. (2013) experimentally studied the single-phase heat transfer characteristics of pulsating flows induced by rolling motion in a circular pipe. The authors show that the pulsating flow induced by rolling motion does not lead to significant variations in cycle-averaged heat transfer characteristics. However, the experimental studies of Murata et al. (2000) and Tan et al. (2009a) show that the heat transfer coefficient of rolling conditions is greater than that of the non-rolling case. Tan et al. (2009a) also show that the heat transfer coefficient of the rolling case increases with an increase in rolling amplitude and frequency. Yan et al., 2010a,b theoretically studied heat transfer with laminar pulsating flow in a channel or tube in rolling motion. The study shows that Nield and Kuznetsov's results cannot be applied to laminar pulsating flows in nuclear power systems under ocean conditions. Moreover, correlations of velocity, temperature and the Nusselt number are given. Yuan et al. (2016) show that the effects of flow rate fluctuations on the average Nusselt number are shaped by the nonlinear relationship between the Nusselt number and Reynolds number in

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Nomenclature

General symbols

t	time (s)
$\bar{T}$	rolling motion period
Δp	pressure drop (Pa)
y	y-axis coordinate (m)
z	z-axis coordinate (m)
g	gravity acceleration (m s^{-2})
W	mass flow rate (kg s^{-1})
u	velocity (m s^{-1})
p	pressure (Pa)
T	temperature (°C)
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	control volume
dp	differential pressure
ts	test section
pp	pressure pipe
add	additional
c_p	specific heat (J kg^{-1} K^{-1})
l	flow direction length
a	additional inertia acceleration (m s^{-2})
i	specific enthalpy (J kg^{-1})
S	unit volume source (J m^{-3})
d	equivalent tube diameter (m)
Re	Reynolds number
Nu	Nusselt number
Pr	Prandtl number
gr	gravitational
roll	rolling motion
fri	frictional
pro	vector projection
loc	local
f	fluid
w	wall

Greek letters

θ	rolling angle (rad)
ω	angular velocity (rad s^{-1})
β	angular acceleration (rad s^{-2})
ρ	density (kg m^{-3})

Vector

a	additional inertia acceleration vector
g	non-inertia system gravity vector
l	flow direction vector
ω	angular velocity vector
β	angular acceleration vector
r	location vector

a transitional flow regime. As is shown above, the effects of rolling motion on characteristics of heat transfer are still contested.

Xing et al. (2013a) found that the transient frictional resistance of a rectangular channel is similar to that observed under non-rolling conditions in high pump head cases, though different patterns are found under low pump head conditions. Furthermore, these researchers found that cycle-averaged frictional resistance is impervious to rolling motion and pump head conditions. However, a theoretical study by Yan et al. (2010c) shows that the effect of rolling motion on the average frictional resistance of a tube should be considerable when rolling motion conditions are very strong. The experimental results of Yuan et al. (2016) show that the average friction factor of a heated rectangular channel increases when flow rates fluctuate in a transitional flow regime under rolling motion. Meanwhile, these researchers observed that the average friction factor under rolling motion is almost the same as that observed under steady conditions in a laminar flow regime due to the linear relationship between flow rates and pressure drop trends. Moreover, Yuan et al. (2016) found that the effects of flow rate fluctuations on the average friction factor are attributed to the nonlinear relationship between pressure drop levels and the Reynolds number in a transitional flow regime. Yan et al. (2014) found that rolling motion barely influences mean frictional and local resistance coefficients in a rod bundle.

Murata et al. (2002) showed that the flow rate of the natural circulation system of a marine reactor changes cyclically with the rolling angle due to the inertial force induced by rolling motion in their experimental study. An experimental investigation by Tan et al. (2009b) also shows that the flow rate of a natural circulation system fluctuates under rolling motion conditions. Yan and Yu (2012) studied characteristics of a natural circulation system subjected to rolling motion experimentally and theoretically. These researchers' results also show that the flow rate of a natural circulation system fluctuates periodically. Moreover, the researchers found that the heat removal capacities of a natural circulation system are less pronounced under drastic rolling motion conditions than under non-rolling conditions. However, the opposite conclusion has been drawn for cases involving low rolling amplitudes. Xing et al. (2013a, 2014a), Tan et al. (2013) and Wang et al. (2014) show that the flow rate under rolling motion conditions oscillates periodically with amplitudes decreasing rapidly as the pump head increases and then stabilizing as the pump head further increases to a certain high level. Yu et al. (2015) studied temperature fluctuations in the mini-rectangular channel of a forced circulation loop under rolling motion. They found that the amplitude of temperature fluctuations decreases initially and then increases but finally decreases again with an increase in the average Reynolds number.

For a single-phase natural circulation system, the flow rate follows a fluctuation mode under rolling motion due to the effects of inertial forces. Moreover, the temperature field is expected to fluctuate. The operation of a natural circulation system thus can be affected by temperature fluctuations. These effects can be described as follows: (1) influencing the accuracy and reliability of data monitoring systems; (2) spurring component aging as a result of cycling thermal stress; (3) impeding the control of reactor core power through reactivity feedback; and (4) in some cases, leading to two-phase flow or coupled instability. However, from our literature review, it can be concluded that some attention has been given to the effects of rolling motion on characteristics of heat transfer and flow resistance. Other studies have focused on flow rate fluctuations and on system heat removal capacities. Furthermore, it is important to note that Yu et al. (2015) study is based on forced circulation conditions. Namely, mechanisms of