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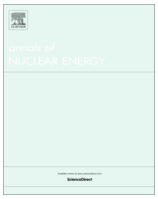

Flow and heat transfer in laminar–turbulent transitional flow regime under rolling motion

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ABSTRACT

Flow and heat transfer characteristics under rolling motion are extremely important to thermohydraulic analysis of offshore nuclear reactors. An experimental study was conducted in a heated rectangular channel to investigate flow and heat transfer in laminar–turbulent transitional flow regime under rolling motion. The results showed that the average friction factor and Nusselt number are higher than that of the corresponding steady flow as the flow rate fluctuates in transitional flow regime. Larger relative flow rate fluctuation was observed under larger rolling amplitude or higher rolling frequency. In the same manner, larger increases of average friction factor and Nusselt number were achieved under larger rolling amplitude or higher rolling frequency. The increases were mainly caused by the flow rate fluctuation through periodic breakdown of laminar flow and development of turbulence in laminar–turbulent transitional flow regime. First, turbulence, which enhances the rate of momentum and energy exchange, occurs near the crest of flow rate wave even the flow is still in laminar flow regime according to the average Reynolds number. Second, as a result of rapid increases of the friction and heat transfer with Reynolds number in transitional flow regime, the increases of the friction and the heat transfer near the crest of flow rate wave are larger than the decreases of them near the trough of flow rate wave, which also contributes to increases of average friction and heat transfer. Additionally, the effect of critical Reynolds number shift under unsteady flow and heating condition on flow and heat transfer was discussed.

1. Introduction

With the application of nuclear reactor in shipping industry (Hirdaris et al., 2014) and development offshore power plants (Lee et al., 2013), thermohydraulic characteristics of nuclear reactor under ocean condition have been receiving increasing attention in recent years. The challenge of thermohydraulic analysis of offshore nuclear reactor lies in the influence of platform motion, including the effects of heave, sway, surge, pitch, roll and yaw.

Since the studies of Ishida et al. (1990) and Murata et al. (1990), a number of studies (Gao et al., 1997; Murata et al., 2002, 2000; Pendyala et al., 2008a,b; Tan et al., 2009a,b; Wang et al., 2013; Xing et al., 2012; Yan, 2012) covering both experiments and mathematical models have been conducted to investigate the effects of platform motion on thermal hydraulics of nuclear reactor. Ma et al. (2011) and Yu et al. (2015) concluded that rolling motion has the most complicated influence on coolant flow and heat transfer. By changing system position and inducing inertia forces, rolling motion can cause flow rate fluctuation. In single phase flow, both pulsatile flow rate and constant flow rate were observed in the experimental studies under rolling motion (Murata et al., 1990, 2000; Tan et al., 2013; Xing et al., 2012; Zhang et al., 2009). The theoretical and CFD results of Yan (2012) indicated that the flow rate fluctuates with a period equals to the rolling period. However, Yan (2012) did not give an evaluation of the amplitude of flow rate fluctuation. To figure out whether flow rate fluctuates under rolling motion and how the flow rate is affected by rolling motion, a series of experimental and theoretical studies were conducted by Tan et al. (2013), Wang et al. (2014) and Xing et al. (2014). And the results showed that flow fluctuation was found dependent on the magnitudes of the driving force and the inertial force caused by the rolling motion. When the driving force is 50 times larger than rolling induced inertial force, the relative amplitude of flow rate fluctuation is within 1%.

Constant flow rate or small flow rate fluctuation is expected in forced flow for its relatively large driving force compared with inertial force induced by rolling motion. Under this condition, the influence of flow fluctuation on the average friction coefficient and heat transfer is very limited (Pendyala et al., 2008a,b; Tan et al., 2013; Wang et al., 2014; Xing et al., 2012).

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Nomenclature

General symbols

a, b	lengths of channel sides (m)
C	constant
D_e	hydraulic diameter (m)
g	gravity acceleration (m/s^2)
h	heat transfer coefficient (w/(m^2 K))
I	electric current (A)
k	conductivity (w/(m K))
L	length between pressure taps (m)
Nu	Nusselt number
p	pressure (Pa)
P	period (s)
q	heat flux (w/m^2)
Q	flow rate (m^3/s)
Re	Reynolds number
T	temperature (°C)
u	velocity (m/s)
U	voltage drop (V)

Greek letters

Δ	difference value
Γ	dimensionless fluctuation amplitude
Λ	cross-regime intensity
λ	friction factor
θ	rolling amplitude (°)
Π	normalized friction factor
ρ	density (kg/m^3)
υ	kinematic viscosity (m^2/s)
Ω	normalized Nusselt number

Subscripts

a	acceleration
b	bulk
c	critical parameter
f	friction
g	gravity
in	inlet
m	measured value
max	maximum
min	minimum
out	outlet
s	steady

Superscript

–	average value

Large flow rate fluctuation commonly occurs in passive safety systems based on natural circulation for their low flow rate conditions. In the case of the laminar pulsating flow, both experimental and theoretical studies revealed that the average frictional resistance is about the same as that in steady state (Aygun and Aydin, 2014; Wang et al., 2014; Xing et al., 2013; Yan, 2012; Zhao and Cheng, 1996a). Meanwhile, theoretical study showed a reduction of heat transfer (Hemida et al., 2002; Yuan et al., 2014, 2016). In turbulent flow regime, the average friction factor was found to increase while heat transfer enhancement cannot be guaranteed under large flow fluctuation (Cho and Hyun, 1990; Elshafei et al., 2008). Both numerical and experimental studies (Cho and Hyun, 1990; Elshafei et al., 2008; Hessami and Zulkifli, 2011) concluded that the average Nusselt number either increases or decreases compared with the steady value, depending on the frequency range. In the concerned frequency range of ocean condition, heat transfer enhancement was observed (Murata et al., 2002; Tan et al., 2009a). Murata et al. (2002) experimentally studied single phase natural circulation in a model reactor and found heat transfer enhancement. Tan et al. (2009) also observed enhanced heat transfer in the experiment on single phase natural circulation. The heat transfer coefficient was found to increase with the rolling amplitude and decreases with rolling period. Regarding the transitional flow regime, adiabatic studies of pulsating flow showed that the average friction coefficient under rolling motion is larger than that under steady condition (Tan et al., 2013; Zhuang et al., 2014). Tan et al. (2013) and Zhuang et al. (2014) concluded that the increase of the average friction coefficient compared with that of steady flow is due to the periodic breakdown of laminar condition near transitional flow regime.

The above literature review indicates that though plenty of studies have been conducted on thermal hydraulics under rolling motion, few of them are focused on average frictional resistance and heat transfer in heated channels in transitional flow regime even though the flow rate fluctuation in this flow regime are generally large enough to make a difference. Therefore, experimental study and analysis were carried out under rolling motion in the present study to clarify the flow and heat transfer characteristics in transitional flow regime.

2. Experimental apparatus

The experimental system consists of the experimental loop, rolling plat form and instrumentation system, which has been previously introduced in literatures (Wang et al., 2014; Yu et al., 2015). Details about the experimental system can be found in the literatures mentioned above. Here, only a brief description of the experimental loop is illustrated (Fig. 1). The fluid was driven by a centrifugal pump. An electrical preheater was applied to control the inlet temperature. The fluid, after being heated in the test section, was cooled in a tube-shell heat exchanger. The system pressure was adjusted by a pressurizer which could be connected to a high pressure nitrogen vessel. The stainless test section is a rectangular channel with an internal cross section of 40×2 mm^2 and a length of 1000 mm.

The narrow side length of the test section was measured by a clearance gauge with an error of ±0.01 mm. The pressure drop was measured by a differential pressure transducer (Xiyi DP5E22M4B1) with a range of 0–50 kPa and an uncertainty of 0.2%. An electromagnetic flow meter (KROHNE OPTIFLUX4000F) with a range of 0–3 m^3/h and an uncertainty of 0.3% was applied to measure the volume flow rate. Eight N-type thermocouples with an uncertainty of 0.1% were applied, two of them were used to measure inlet and outlet bulk temperature and six of them were attached to the exterior wall surface to measure wall temperature.

3. Experimental procedure and data processing

3.1. Experimental procedure

System pressure was controlled by a nitrogen supply system and a relief valve. The average inlet and outlet fluid temperatures were maintained constant by adjusting power supply of the