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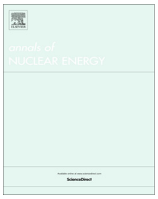

Effects of rolling motion on thermal–hydraulic characteristics of boiling flow in rectangular narrow channel

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ABSTRACT

Experimental investigations on thermal–hydraulic characteristics of boiling flow in a rectangular narrow channel under rolling motion conditions are carried out. This experiment is designed to elucidate the phenomena of boiling flow under rolling motion and to give the corresponding rational explanations. The results show that the amplitudes of fluctuations of pressure drop, flow rate, fluid and wall temperatures, and boiling heat transfer coefficient increase with the increasing of rolling amplitude and rolling period. The phase difference of flow rate fluctuation and pressure drop fluctuation is 1/4 period, and the saturated water temperature fluctuations of the test section delay 2–3 s behind the pressure drop fluctuations. The time average boiling heat transfer coefficients of the rectangular narrow channel under rolling motion are equal to those under static conditions. The amplitude of boiling heat transfer coefficient of test section increases with increasing heat flux and flow rate, while decreases with increasing system pressure.

1. Introduction

The first nuclear-power submarine launched successfully in the United States in 1954, and then the nuclear power are widely used in the ship and submarine. Affected by the ocean wave, the ship will generate rolling, heaving and pitching motions (Ishida et al., 1990, 1995). The effects of ship motions should be taken into account when calculating the thermal–hydraulic performance of reactor systems in the ship. The rolling motion of the ship can change the position of the primary coolant system nonlinearly and introduce the additional inertial force (Tan et al., 2009a,b; Wang et al., 2014). This means that different amplitudes, periods and positions of the rolling motion have different effects in different system compositions. Therefore, the experimental researches of the effects of rolling motion on the thermal–hydraulic characteristics of marine nuclear power plant have the practical significance.

In order to investigate the effects of rolling motion on the thermal–hydraulic characteristics of natural circulation, a series of single-phase natural circulation experimental tests under rolling motion condition are performed by Ishida and Yoritsune (2002), Murata et al. (2002, 2012), Tan et al. (2009a,b, 2013). The results of their experiments show that the additional inertial force caused by the rolling motion easily induces the fluctuations of natural circulation flow rate. Series simulation and experiments about the effects of ship motions on the natural circulation in deep sea research reactor system are performed by Ishida and Yoritsune (2002). The result show that ship inclination induces the natural circulation flow rate decrease and heaving makes the core flow rate and reactor power oscillation. Because of resonance of the natural circulation and the heaving, the oscillation amplitudes of flow rate have a peak at the heaving period of 5 s. The experimental researches on the heat transfer characteristics of natural circulation under rolling motion are performed by Murata et al. (2002, 2012). The research show that the rolling motion enhanced heat transfer in the core and the enhancement caused by the internal flow rate due to the rolling motion. The heat transfer correlation in the core is well correlated with the Richardson number for rolling motion and the Richardson number is classified into three regimes to predict the heat transfer correlation. Theoretical and experimental studies on natural circulation flow and heat transfer under rolling motion condition are conducted by Tan et al. (2009a,b, 2013). The results show that the average mass flow rate of natural circulation decreases with the increase of amplitude and frequency of the rolling motion. Rolling motion enhances the heat transfer, and the average heat transfer coefficients of natural circulation increase with the amplitude and frequency of the rolling motion. Under rolling motion condition, the similar results also

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Nomenclature

A	rolling amplitude, °
D_e	hydraulic diameter, m
h_{in}	inlet enthalpy, kJ/kg
h_{out}	outlet enthalpy, kJ/kg
h_{tp}	boiling heat transfer coefficient, kw/m^2 °C
I	heating current, A
k_w	thermal conductivity, kw/m °C
m	mass flow rate, kg/s
P	system pressure, MPa
q	heat flux, kw/m^2
T	rolling period, s
T_{sat}	saturated temperature, °C
T_w	wall temperature, °C
t	time, s
U	heating voltage, V

Greeks

β	angular acceleration, rad^2/s
δ	thickness of the wall, m
η	thermal efficiency
θ	rolling angle, rad
ω	angular velocity, rad/s
Φ	volumetric heat, kw/m^3

Subscripts

max	the maximum value
th	thermocouple
pr	pressure tube

can be found in theoretical works conducted by Yan et al. (2010, 2011), Yan and Gu (2011). The theoretical studies also show that the fluctuations of flow rate and heat transfer coefficient of natural circulation vary with the rolling amplitude and rolling frequency.

The fluctuations of flow rate and heat transfer coefficient are confirmed in single-phase natural circulation flows under rolling motion condition, but in forced circulation, the phenomenon of flow rate and heat transfer coefficient under rolling motion is not very clear. The experimental research of forced circulation under rolling motion condition has been conducted by Tan et al. (2013) and Xing et al. (2012, 2013). In the study of Tan et al. (2013), the flow rate has the significant fluctuation and the amplitude of flow rate fluctuations increases with increasing rolling amplitude and valve opening while decreases with the increase of the rolling period and driving head. However, the experiment of Xing et al. (2012, 2013) found that the amplitude of the flow rate fluctuation is very small and could be neglected in the forced circulation. Therefore, the thermal–hydraulic characteristics of forced circulation under rolling motion condition are not very confirmed, especially in boiling region.

Compact heat exchangers are widely adopted in the ship because of their small volume and large heat transfer area, especially, the heat exchanging performance of the compact heat exchangers is high. Mostly, a compact heat exchanger is composed of an array of rectangular narrow channels and the gap size is small (in the range of 0.5–2 mm). Experimental research and theoretical analysis of the thermal–hydraulic characteristics of rectangular narrow channel are performed by Mishima et al. (1993), Zhang et al. (2004), Lee and Lee (2001), Warrier et al. (2002), Ma et al. (2011) and Wang et al. (2012). The local heat transfer coefficient is an important parameter for the compact heat exchanger, and the amplitude of the coefficient fluctuation is very important for the design of the compact heat exchanger used in the ship. Therefore, the local heat transfer coefficient should be taken into account when analyze the thermal–hydraulic characteristics of the boiling flow. However, only a limited number of works have been reported on the thermal–hydraulic characteristics of boiling region in rectangular narrow channel under rolling motion condition.

2. Experimental setup and data reduction

The schematic diagram of the mechanical rolling thermal–hydraulic experimental facility is shown in Fig. 1. The experimental setup is comprised of experimental loop, rolling platform and instrumentation system. Detailed introduction of the experimental facility will be given in the following sections.

2.1. Experimental loop

The experimental loop is schematically illustrated in Fig. 1. The maximum flow rate is 3 m^3/h, maximum system pressure is 3 MPa and the maximum load of the rolling platform is 2 tons. The experimental loop is comprised of experimental hot loop and experimental cooling loop. The experimental cooling loop consists of two circulating water pumps, a water tank and a cooling tower. The experimental cooling loop is mainly used to cool the hot fluid in the experimental hot loop. The experimental cooling loop and hot loop are connected by the condenser. Experimental hot loop consists of a main pump, a pressurizer, a pre-heater, an inlet valve, a filter, a test section, a condenser, computers and a DC power supply. The DC power supply is used to heat the test section, and the highest electric power is 100 kW. The flow rate can be adjusted by changing the rotating speed of the main pump or changing the opening of the throttle valve. The pressurizer linked with a high-pressure nitrogen cylinder is used to maintain the system pressure. The pre-heater is used to heat the fluid and the highest electric power is 45 kW. The test section contains 7 thermocouples and 3 pressure tubes. They are used to measure the wall temperature of test section and the pressure drop of the fluid respectively. Therefore, when the experimental loop is running, the fluid is heated in pre-heater at first, and then flow into the test section and heated continually by the DC power supply. At the same time, the wall temperature and the pressure drop are measured and displayed on the computer. Then the hot fluid flows into the condenser where it can be cooled. Finally, the cooling water returns to the pre-heater and begins the next cycle.

2.2. Rolling platform

The rolling platform consists of a three-phase asynchronous motor, a reduction gearbox, a crank and rocker mechanism. The rolling platform is driven by the three-phase asynchronous motor and reduction gearbox. The period of the rolling motion is controlled by the frequency of the motor. The crank and rocker mechanism designed according to Glasgow Hove Theorem is schematically illustrated in Fig. 2. Different rolling amplitudes can be acquired by changing the length of the rocker, when the rocker moves to A or B position the amplitude of the rolling platform reaches the maximum. The motion of a ship at sea can be simulated by the rolling platform. The instantaneous rolling amplitude can be approximated by:

$$\theta_t = \theta_{\max} \sin(2\pi t/T) \tag{1}$$