Effect of steam quality on two-phase flow in a natural circulation loop*

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Abstract Test pressures are 1.0~4.0 MPa, heating powers 27~190 kW, inlet subcoolings 5~80°C, water used as coolant, and steam quality at the outlet of test section is less than 0.05. These test conditions cover the parameters for a typical 200 MW heating reactor. The experimental results show that the steam quality is the dominant factor in a natural circulation system with low pressure and low steam quality about the effect of system pressure, heating power and inlet subcooling on the flow rate, relative oscilatory amplitude and oscilatory region of flow rate.

Keywords Heating reactor, Two-phase flow, Instability, Natural circulation

1 Introduction

As well known, in systems and components with two-phase flow, such as boilers, steam generators, nuclear reactors and some chemical facilities, two-phase flow instabilities may appear under certain conditions[1]. The parameter change caused by two-phase flow instability could affect local heat transfer characteristics, induce boiling crisis, cause mechanical vibration and disturb control systems.

A slightly boiling integrated-type natural circulation reactor is expected to be one of the advanced design of heating reactors, a few countries including China, Switzerland and Russia have done some research work, but few results have been published on the thermalhydraulic problems[2,3], and all over the world, to date, only one of this kind of test heating reactor has been operated in the Institute of Nuclear Energy Technology (INET) of Tsinghua University in China (a same kind of commercial heating reactor will be constructed in China in the next few years[4]). In the heating reactor designed by INET the coolant water, with relatively low system pressure P (less than 2.5 MPa) and low steam quality X_e at the exit of the core (less than 0.05), flows through the system under natural circulation condition, because of the long riser above the core a small perturbation of steam quality at the exit of the reactor core will lead to a relatively large change of the void fraction in the riser, so do the driving force and the mass flow rate, under certain operation conditions, thermal-hydraulic parameter oscillation may be excited.

In order to accumulate experimental data for verification of the models and codes used in design and safety analysis of this type of reactor, to understand thoroughly the characteristics of the second type density wave oscillation and to predict the threshold of flow instability, a full scale simulating experimental system HRTL-200[5] to the prototype reactor in the flow direction has been constructed in INET and operated under test conditions covering a broad range of parameters for a typical prototype heating reactor. Some of the investigation results coming from the HRTL-200 test loop is presented in this paper.

2 Test system

The schematic diagram of the HRTL-200 experimental system and the details of the primary loop are shown in Fig.1. The test system consists of the primary loop, secondary flow loop, ancillary cooling loop, electric heating system and measuring system. The primary loop is composed of test section, riser, steam separator, steam condenser, heat exchanger, pressurizer, downcomer, valves, pump and connection tubes. The system could be operated in natural or forced circulation mode. The

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vertical test section consists of 9 electrically heated rods with uniform power distribution, the stone insulation layer and pressure vessel. The heated rods are made from stainless steel tube with 10 mm OD, and they are arranged in 3×3 cluster with a pitch of 13.3 mm. The riser height is 5 000 mm and the total height of the test loop is about 10 000 mm.

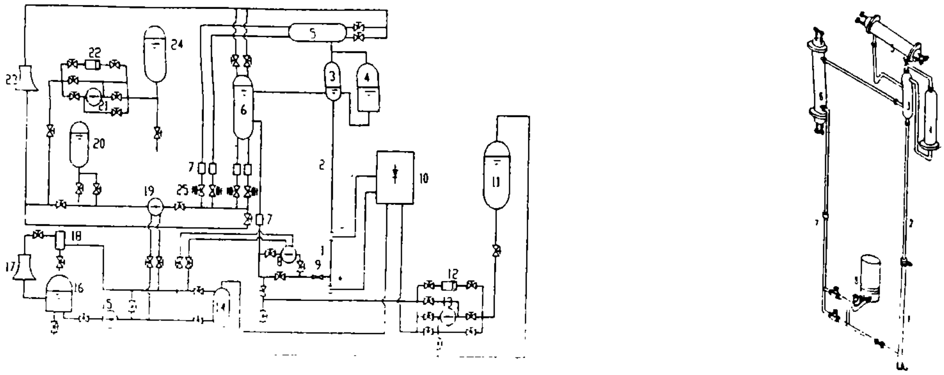

Fig.1 Principle flow diagram of the test system and the primary test loop
1. Test section 2. Riser 3. Separator 4. Pressurizer 5. Condenser 6. Heat exchanger 7. Flow rate meter 8. Pump 9. Venture tube

3 Experimental results

3.1 Stable flow characteristics of system

Keeping system pressure P, inlet resistance coefficient K_{in} and inlet subcooling ΔT_{sub} constant, the mass flow rate G of the natural circulation loop will change with the increase in the heating power W. The experimental results under the different inlet subcoolings are given in Fig.2. It reveals that under this low pressure an equal increase in the heating power will lead to different increase in the mass flow rate if other parameters are constant. At the low heating power portion with the increase in the heating power the mass flow rate of the natural circulation increases fast, at the high power portion the increase in the mass flow rate becomes slow. This is in agreement with the correlation between steam quality and void fraction at the low pressure. Because an increase in the heating power leads to an increase in steam quality at the exit of the test section, and consequently to an increase in the void fraction in the riser, but as well known, under the low pressure the void fraction increases with the steam quality fast at the low steam quality portion, and slowly at the high steam quality portion. This will lead to the same change tendency for the driving force of the natural circulation, so does the mass flow rate. At the higher power portion the increase in the steam quality would lead to increase in the two-phase flow resistance, so the mass flow rate decreases. Fig.3 show the influence of the system pressure on the mass flow rate of the natural circulation loop under the different subcoolings.

Fig.4 shows that for given geometry, system pressure and inlet resistance coefficient, the mass flow rate was found to be only dependent on the exit steam quality of the test section under the different heating power.

3.2 Two-phase flow instability

If system pressure, inlet resistance coefficient and heating power are constant during the experiments, the inlet subcooling of primary loop coolant will change with the change in the secondary flow rate through the heat exchanger. Under high inlet subcoolings, the flow is in single phase region, the system is stable. In certain inlet subcooling region, with the decrease in the inlet subcooling, the system becomes unstable, the mass flow rate will oscillate in cyclic mode with certain even amplitude and relatively low frequency, Fig.5 shows the typical mass flow oscillation wave via time t. If the inlet subcooling is continually reduced the oscillation amplitude will increase first and then decrease after reaching a maximum peak value, and at last the system enters the stable region again under small inlet subcoolins. The system was defined as instability if the relative amplitude $\Delta G/G$ of mass flow rate is greater than 0.05.

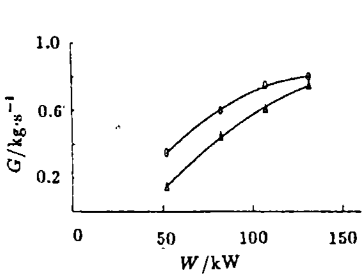

Fig.2 Effect of subcooling and heating power on mass flow rate
O: $\Delta T_{sub} = 20°C$, $P = 1.5\,MPa$, Δ : $\Delta T_{sub} = 30°C$, $K_{in} = 25$

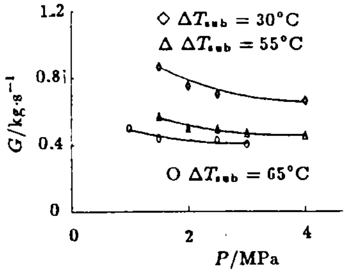

Fig.3 Effect of system pressure on mass flow rate
$W = 131\,kW$, $K_{in} = 25$

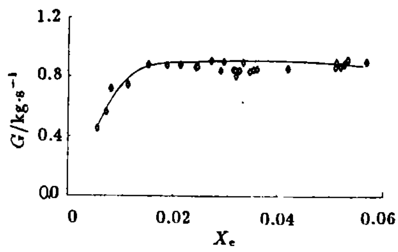

Fig.4 Mass flow rate vs exit steam quality
$P = 1.5\,MPa$, $K_{in} = 25$, $W = 27 \sim 188\,kW$

Fig.6 shows that the higher the system pressure is, the lower the relative amplitude $\Delta G/G$ of mass flow rate is, and the wider the stable region is.

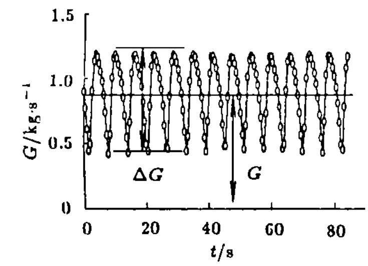

Fig.5 Typical oscillation of mass flow rate
$P = 1.5\,MPa$, $\Delta T_{sub} = 26.6°C$, $W = 132\,kW$, $K_{in}=25$

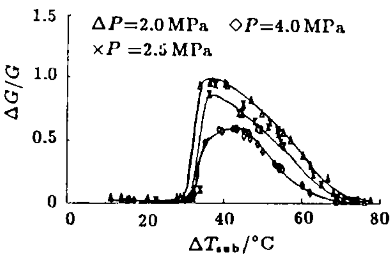

Fig.6 Effect of system pressure on instability region
$W = 131\,kW$, $K_{in} = 25$

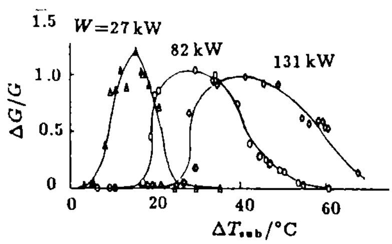

Fig.7 Relative amplitude of mass flow rate vs inlet subcooling
$P = 1.5$ MPa $K_{in} = 25$

Fig.7 shows the dependence of the unstable region and the relative amplitude of the mass flow rate on the heating power. From Fig.7 it is obvious that if the system pressure and inlet resistance coefficient are constant with the increase in the heating power the unstable region of the mass flow rate moves towards the larger inlet subcooling, and the largest relative amplitude of flow rate changes a little.

From Fig.7, according to the definition of the threshold value of instability, on every test curve of constant heating power, two important inlet subcooling values describing the small subcooling boundary point and high subcooling boundary point respectively could be obtained. Based on the experimental results the stability map of the system has been derived (see Fig.8). The picture clearly reveals the operation characteristics of the system. For nuclear reactors the operation conditions are similar to those of the Fig.8, that is to say, the system pressure, the inlet resistance coefficient and geometry are unchangeable, but the inlet subcooling changes with the change in the power, such as during the start period of the reactor. The heating reactors should work in the region of small steam quality, Fig.8 is useful for the operation members.

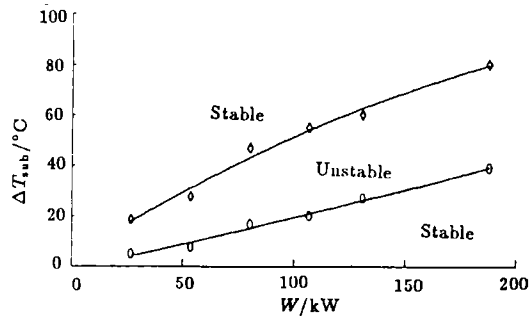

Fig.8 Stability map of the system
$P = 1.5\,\text{MPa}$, $K_{\text{in}} = 25$

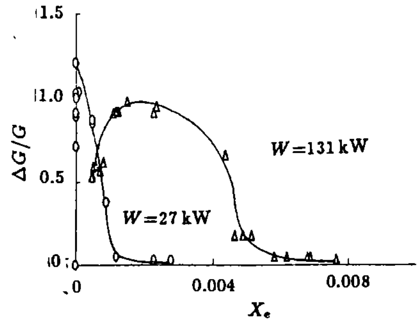

Fig.9 Effect of steam quality on instability
$P = 1.5\,\text{MPa}$, $K_{\text{in}} = 25$

Under different heating powers the dependence of relative amplitude of mass flow rate on the steam quality at the exit of the heated section is shown in Fig.9. This figure demonstrates that all unstable points with relative amplitudes of mass flow rate greater than 0.05 lie in the low steam quality region where steam quality X_e is less than 0.01. It reveals that there is an unstable region in the range of low steam quality and the steam quality is also the dominant factor in the unstable region.

4 Conclusions

Under certain geometric conditions and operating parameters, a self-sustaining, low frequency, even amplitude mass flow oscillation may be excited by very low steam mass qualities in a low pressure system with natural circulation.

The steam quality at the outlet of the heated section is considered to be a dominant factor for the hydrodynamic stability of a low steam quality two-phase natural circulation system at low pressure.

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