Flashing and flashing coupled density wave oscillation in natural circulation system*

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Abstract The phenomenon and mechanism of different kinds of two-phase flow instabilities, namely geysering, flashing instability and flashing coupled density wave instability are firstly well interpreted by the experiment performed on the test loop (HRTL-5) simulating the 5-MW reactor. The flashing coupled density wave instability is analyzed by using an one-dimensional non-thermoequilibrium two-phase flow drift model computer code. Calculation results are in good agreement with the experimental.

Keywords Flow instability, Flashing instability, 5 MW heating reactor

1 Introduction

A 5-MW nuclear heating reactor[1] developed by Institute of Nuclear Energy Technology (INET) has been in operation since 1989. In order to investigate the thermohydraulic behavior of natural circulation in the primary loop of the 5 MW reactor, a test loop HRTL-5 simulating its geometry and system design was erected at INET. Several kinds of flow instabilities have been studied, for example, at low system pressure (p <0.3 MPa), geysering and flashing in a natural circulation system with a long, non-heated riser can cause flow instability, namely flashing instability; at higher system pressure (0.3 MPa< p <1.5 MPa) pure flashing instability does not occur, but coupled with density wave instability, namely flashing coupled density wave instability does.

Since the 1950's with the beginning of commercialization of nuclear reactors, the interest in two-phase low instability studies started growing internationally. J. A. Boure *et al.*[2] made a clear classification of flow instabilities at that time. Most of these instabilities mentioned by Boure concerned forced circulation, and the density wave instability was concerning high-steam quality for the BWR conditions. Fukuda and Kobori[3] studied both low-(type I) and high-steam quality (type II) density wave instabilities for both natural and forced circulations. Another kind of instability called geysering was also mentioned by Boure[2] and Aritomi *et al.*[4]

2 Experimental system

The primary loop of HRTL-5 consists of the following parts, two parallel vertically heated sections, risers and steam separators, one heat exchanger, one steam condenser and downcomer, throttle valves, and connection tubes. Three pairs of glass windows are installed at the exit of the heated section, inlet and exit of the riser, respectively. The total height of the test system is about 7 m. Table 1 lists the important parameters of the test loop HRTL-5.

Table 1 Main parameters of the test loop HRTL-5

Working fluid	Water
System pressure	<2.0 MPa
Fluid temperature	<200° C
Heat flux	<0.6 MW·m^{-2}
Inlet subcooling	>2 K
Height of heated section	0.58 m
Hydraulic diameter of heated section	10.2 mm
Diameter of heated rods	10 mm
Height of riser	3.0 m
Resistance coefficient at the inlet of heated section	10~100

3 Analytical approach

The investigated system consists of a subcooled single-phase region, a subcooled boiling region, a bulk boiling region in the heated section, a two-phase region in the adiabatic riser,

*National "85" Key Project
Manuscript received date: 1996-06-20

which is divided into smaller sections in order to calculate void flashing exactly, and a single-phase region in the subcooler and down-comer.

Typical two-phase flow patterns for heated section and riser are shown in Fig.1. The subcooled single-phase fluid enters the heated section at $Z=0$. Non-equilibrium boiling begins at Z_N, saturated boiling at Z_S (Fig.1a). When the saturation temperature is not reached at the end of heated section Z_H, the non-equilibrium steam condenses partially or completely (Fig.1b) at the inlet of the riser, thereby increasing the liquid temperature. If the liquid is still subcooled (Fig.1b), flowing up the riser and finally it reaches saturation temperature due to gravity pressure drop, and void flashing begins at Z_F. The computer simulation rests on an one-dimensional two-phase flow drift model[5] with the conservation equations for mass, steam, energy, and momentum. The Clausius-Clapeyron equation is used for the flashing front.

4 Flashing coupled density wave oscillation

The designed pressure of the 5 MW nuclear heating reactor is 1.5 MPa. In order to get a general thermodynamic understanding of the reactor under different conditions, it is of great importance to simulate the thermodynamic behavior outside the reactor by a test system. The following work was done under the constant heat flux and system pressure (the same as the designed values of the 5 MW reactor), and different inlet temperatures. The dependency of relative mass flow rate amplitude on the inlet subcooling is shown in Fig.2. Through visual investigation we get the following understanding on the thermodynamic behavior of the 5 MW reactor:

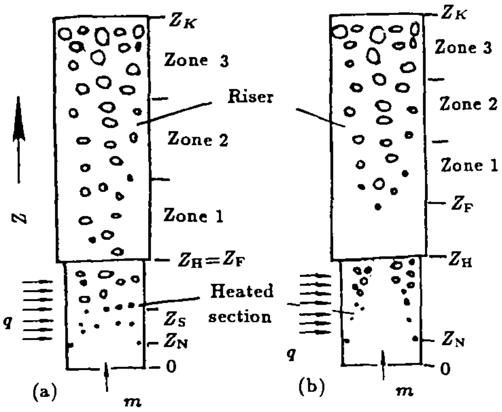

Fig.1 Two-phase flow pattern in the test loop
(a) Non-equilibrium and saturated boiling in the heated section; void flashing in the riser starting at $Z_F = Z_H$. (b) Only non-equilibrium boiling in the heated section; void flashing in the riser starting at $Z_F > Z_H$

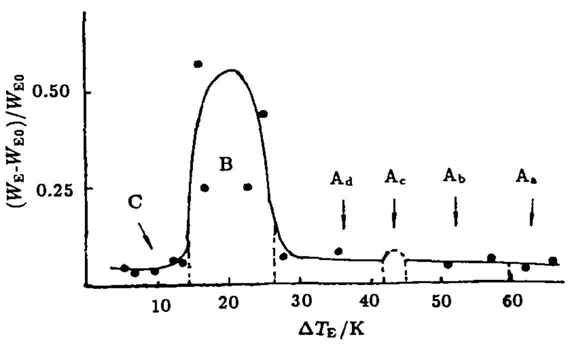

Fig.2 Experimental result for relative oscillation amplitude under the condition of $p=1.5$ MPa, $q=200$ kW/m^2

a. In single phase flow region A_a, no subcooled boiling can be observed, flow is stable.

b. In subcooled boiling stable flow region A_b, warm fluid disturbance can be seen near the heated rods. Steam bubbles appear at the wall of the heated rods, but no bubbles leaving the surface of the rods can be seen.

c. In flow excursion region A_c, bubbles leaving the wall at the upper part of the heated section can be seen. Flow excursion occurs in this region.[5]

d. In subcooled boiling stable region A_d, it is observed that not all bubbles are ejected from the surface condense, some of them enter the riser, and the flow is stable.

e. In flashing coupled density wave oscillation region B, subcooled boiling vapors are partly condensed at the inlet of the riser. Fluid reaches saturation in the riser. Void flashing occurs, and the flow is unstable. The flashing coupled density wave oscillation is discussed later in detail.

f. In bulk boiling stable region C, water reaches saturation at the exit of the riser. Flow is stable.

The mechanism of flashing coupled density wave flow oscillation is described as follows. In the case of a little decrease in the inlet flow velocity, the steam volume in heated section and riser increases with a certain delay. The growing difference in mass density between the single phase flow in the downcomer and the two-phase rising flow accelerates the natural circulation in the closed loop. Thereby, the original negative perturbation in the flow velocity is gradually balanced and overbalanced, so that a positive deviation of the flow velocity results. In this way flow oscillations can develop. If the excited oscillations finally die away, the system is stable; if asymptotically flow oscillations with a constant amplitude (limit cycle) remain, the system is unstable. Self sustained oscillations are favored, if changes in the pressure drop in two- and single-phase sections partially compensate each other, as a result, a suitable phase lags. Fig.3 represents calculated relative changes in the liquid velocity W_E at the entrance of the heated section after a short perturbation starting at $t=0$. The examples differ in the subcooling at the entrance of the heated section: $T_S - T_E$, where T_S is saturation temperature, T_E liquid one at $Z=0$. For subcoolings in $0 \leq T_S - T_E < 14.6\,\text{K}$ there exist a stable two-phase flow in the test loop at system pressure of 1.5 MPa and a heat flux of 200 kW/m^2 (see region C in Fig.2). Correspondingly, at a subcooling of 14.0 K the oscillation amplitudes decay. The amplitude ratio of consecutive oscillations, i.e. the decay ratio Y_{i+1}/Y_i (Fig.3) is a measure of the flow stability. If the inlet subcooling is increased to 14.6 K the decay ratio approaches to 1 (compare instability boundary in Fig.2). Using this criterion, the stability boundary can be determined from the analysis of the non-linear system in the time domain. A measure of the instability is the amplitude of the limit cycle. For instance, an increase in the inlet subcooling from 14.6 K to 14.8 K results in an increase in the oscillation amplitude from 0.03 to 0.11 (Fig.3). At high subcooling a stable single-phase flow exists. So, if we continue to increase the subcooling in the instability region, a second stability boundary is reached. According to the calculating model this upper boundary is close to $T_S - T_E = 26\,\text{K}$. The analysis shows that for the instability range of $14.6\,\text{K} \leq T_S - T_E \geq 26\,\text{K}$ only non-equilibrium boiling occurs in the heated section; the saturation temperature is never reached at Z_H. The calculating results for the flashing coupled density wave instability boundary ($T_S - T_E = 14.6\,\text{K}$) in Fig.3 are in good agreement with those of experiment in Fig.2.

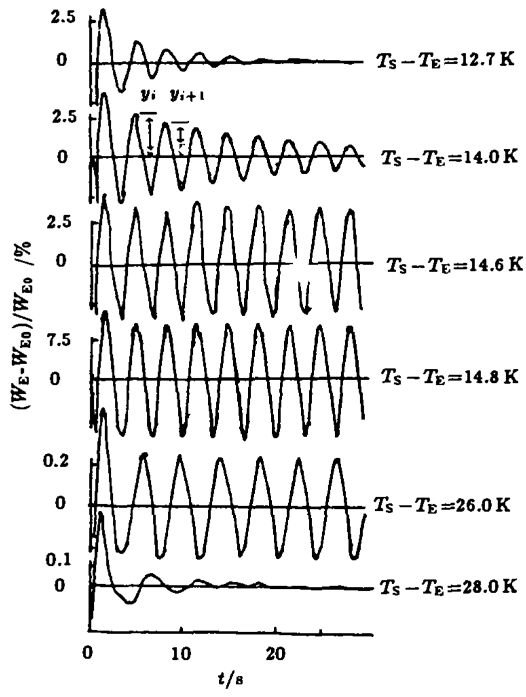

Fig.3 Relative oscillation amplitude of the inlet velocity W_E for different inlet subcoolings $p=1.5\,\text{MPa}$, $q=200\,\text{kW/m}^2$

The increase in the volumetric steam fraction by void flashing is traced in Fig.4 through several sub-zones of the riser. The propagation of the density wave in the riser is evident from the time lag between amplitude maxima in consecutive zones. It depends on the velocity of the steam. At low instability boundary ($T_S - T_E$=14.6 K), the void fraction at the exit (0.16) is obviously greater than that at the inlet (0.11) of the riser. At the higher instability boundary ($T_S - T_E$=26 K), there is little void fraction (0.01) at the inlet, but about 0.055 at the exit of the riser. So Fig.4 shows the important behavior of the flashing coupled density wave instability.

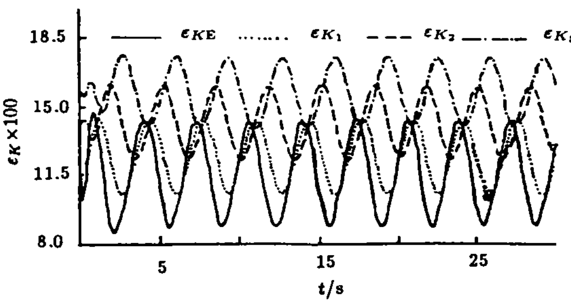

Fig.4 Void fraction in three sub-zones of the riser, close to the stability boundary
p=1.5 MPa, q=200 kW/m^2

5 Flashing instability

5.1 Differences between flashing instability and geysering

The flashing instability is different from the geysering mentioned by Boure and Aritomi in the following aspects.

5.1.1 Phenomenon

The vapors which cause flashing instability are first generated at the top of the long non-heated riser, then develop downwards along the riser, while by geysering the vapors are formed only in the heated section, and condensed at the inlet of the riser as they flow upwards. The mass flow rate by flashing instability is much greater than that by geysering, and it oscillates gradually due to the relatively long process of flashing generation, development and disappearance in the riser, unlike that of pulse-like oscillation due to the sudden condensation of a big subcooled vapor at the inlet of the riser by geysering.

5.1.2 Cause of vapor generation

The vapors by flashing are formed purely by the decrease in hydrostatic head as water flows upwards while they are generated first in the heated section through heating by geysering.

5.1.3 State of thermal condition

By flashing the vapors are formed in the non-heated long riser as the upwards flowing water reaches its local saturation temperature, therefore the vapors are in thermal equilibrium condition, and they are not condensed during the process of oscillation. By geysering the vapors are always in thermal non-equilibrium condition.

5.1.4 Mechanism of oscillation

Flashing instability is caused by the change in the driving force due to fluid vaporizing (flashing) at the top of the long non-heated riser, flashed vapor downwards developing and flowing out from the riser, while geysering is caused by the generation, detachment, growth and condensation of subcooled vapor in the heated section and at the inlet of the riser.

5.1.5 Geometry condition

The flashing instability described in the present work was performed at single channel condition of HRTL-5, which has a short heated section (0.58 m) and a long non-heated riser (3.0 m). By shorter non-heated riser (0.25~0.75 m by Aritomi[4]) and by closed end system (by Boure[2]) it is difficult to investigate flashing instability. Consequently, flashing instability has never well investigated at nuclear reactor conditions.

The relative mass flow amplitude map at 0.1 MPa is similar to Fig.2. But there is not the flow excursion region A_c, the region B is not the flashing coupled density wave instability region, but is flashing instability dominated region.

5.2 Flashing instability

Fig.5 shows the experimental result of flashing instability accompanied by geysering. The geysering in HRTL-5 is not the same as that mentioned by Boure[2] and Aritomi[4]. Geysering occurs at certain inlet subcooling region. This kind of oscillation is also caused by vapor generation, growth, detachment and condensation. The mass flow rate (m) oscillates with high peak values, like pulses without a regular period. Very loud "explosion-like" sounds occur as vapor condenses in the inlet of the riser, and no vapor was observed in its upper part during this oscillation. The condensation of the subcooled vapor results in a strong flow disturbance, which, acting as a pressure wave, propagates in the system at the velocity of sound. The energy of the pressure wave is released when it passes valves and other components in the system. Very strong mechanical vibrations of the whole test facility, resulting from the energy release, have been observed during geysering. As the inlet subcooling decreases, flashing instability occurs and is accompanied by geysering. The fluid temperature in the riser increases gradually during geysering because of continuous condensation of subcooled vapor from the heated section. There are few vapors in the upper part of the riser because of the condensation. The fluid temperature finally reaches its saturation one when the flow reaches the exit of the riser, then at this position flashing occurs, namely, vapors are generated here. Due to the flashing below the exit of the riser the pressure decreases and then fluid also flashes there. Because the propagation velocity of the flashing is much faster than that of the flow, this flashing phenomenon can therefore develop along the riser to its lower part. The flashed vapors are uniform unlike those of subcooled boiling in the heated section. There are more vapors in the upper part than in the lower part of the riser during the process of flashing. At the same time, the mass flow rate increases significantly due to the increase in the system driving head. As this mass flow rate increases continuously in the heated section, the subcooled boiling disappears, and the cold water enters the riser. Flashing vanishes when the hot water originally contained in the riser flows out. The mass flow rate decreases as flashing disappears, followed by the start of subcooled boiling in the heated section. The subsequent steps are subcooled vapor generation, detachment and condensation in the heated section and at the inlet of the riser, no periodical geysering, temperature increase in the riser during geysering, and the next flashing instability.

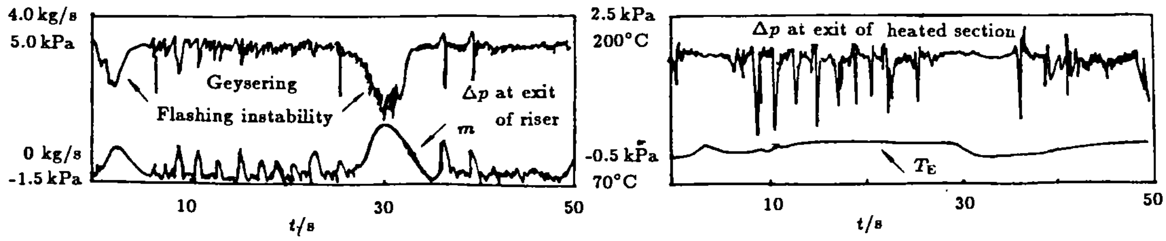

Fig.5 Geysering and flashing instability

6 Conclusion

a. Flashing instability occurs in the system with long non-heated riser at low system pressure (p <0.3 MPa) in the present work.

b. At higher system pressure (0.3 MPa< p <1.5 MPa) pure flashing instability does not occur, but coupling density wave instability does.

c. Flashing coupled density wave instability can be well predicted by analyses.

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