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CHINA NUCLEAR SCIENCE AND TECHNOLOGY REPORT

低温核供热堆流动特性分析

ANALYSIS ON FLOW CHARACTERISTIC OF NUCLEAR HEATING REACTOR

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姜胜耀：清华大学核能技术设计研究院教授，1984 年毕业于清华大学，1986 年在清华大学获硕士学位，1994 年在德国斯图加特大学获博士学位。

JIANG Shengyao: Professor of Institute of Nuclear Energy Technology, Tsinghua University. Graduated from Tsinghua University in 1984 and received Ph. D degree at Stuttgart University of Germany in 1994.

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低温核供热堆流动特性分析

姜胜耀　吴莘馨

（清华大学核能技术设计研究院，北京）

摘　要

实验研究在 5 MW 核供热反应堆模拟热工水力学实验回路 HRTL-5 上进行。分析计算基于带有质量，蒸汽质量，能量及动量守恒方程的一维两相流漂移模型。给出了在不同系统压力，进口过冷度及热流密度条件下的稳态和动态分析结果。研究结果表明：加热段中的过冷沸腾及上升段中的闪蒸对空泡份额分布及流动稳定性有重要影响，特别是在低压条件下；在相当宽的两相流条件下，加热段中只发生过冷沸腾；对于沸水设计工况的 5 MW 低温堆，其堆芯出口温度尚未达到饱和。描述了两相流振荡机理，即“零阻降”机理。在进口过冷度相当宽范围内（$0K<\Delta T<28$ K），对系统流条件，存在 3 个区域，即稳定的两相流，整体和过冷沸腾不稳定流和过冷沸腾以及单相稳定流。给出了系统流量在小热流密度扰动下的响应特性。在此基础上给出了稳定边界图的计算和实验值。

Analysis on Flow Characteristic of Nuclear Heating Reactor

JIANG Shengyao WU Xinxin
(Institute of Nuclear Energy Technology of Tsinghua University, Beijing)

ABSTRACT

The experiment was carried out on the test loop HRTL-5, which simulates the geometry and system design of a 5 MW Nuclear heating reactor. The analysis was based on a one-dimensional two-phase flow drift model with conservation equations for mass, steam mass, energy and momentum. Clausius-Clapeyron equation was used for the calculation of flashing front in the riser. A set of ordinary equation, which describes the behavior of two-phase flow in the natural circulation system, was derived through integration of the above conservation equations in subcooled boiling region, bulk boiling region in the heated section and in the riser. The method of time-domain was used for the calculation. Both static and dynamic results are presented. System pressure, inlet subcooling and heat flux are varied as input parameters. The results show that, firstly, subcooled boiling in the heated section and void flashing in the riser have significant influence on the distribution of the void fraction, mass flow rate and stability of the system, especially at lower pressure, secondly, in a wide range of two-phase flow conditions, only subcooled boiling occurs in the heated section. For the designed two-phase regime operation of the 5 MW nuclear heating reactor, the temperature at the core exit has not reaches its saturation value. Thirdly, the mechanism of two-phase flow oscillation, namely," zero-pressure-drop", is described. In the wide range of inlet subcooling (0 K$<\Delta T<$28 K) there exists three regions for system flow condition, namely, (1) stable two-phase flow, (2) bulk and subcooled boiling unstable flow, (3) subcooled boiling and single phase stable flow. The response of mass flow rate, after a small disturbance in the heat flux, is showed in the above inlet subcooling range, and based on it the instability map of the system is given through experiment and calculation.

INTRODUCTION

Two-phase flow systems have widely used in nuclear power plants (especially in boiling water reactors), industrial boilers, chemical installations etc. Many investigations of two-phase flow, mainly of forced two-phase flow circulation, have been carried out. Studies on natural circulation two-phase flow, most of them with high system pressure, have also been performed.

In recent years, along with the development of nuclear heating reactors, two-phase flows with natural circulation, low pressures and low steam quality have been brought to more attention and have become an important area of research.

A nuclear heating test reactor (5 MW) developed by the Institute of Nuclear Energy and Technology (INET) has been in operation since 1989[1]. Its primary system operates at low pressure (1.5 MPa), low steam quality, and with natural circulation. The steam quality at the exit of the reactor core is less than 1%, the void fraction due to low system pressure is relatively high. A long riser above the fuel assemblies accommodates the steam-water mixture leaving the reactor core and provides the driving force for the natural circulation. In order to investigate the hydrodynamic features of natural circulation in the primary loop of a pool-type and integrated vessel-type low temperature heating reactor (5 MW), a test loop (HRTL-5), simulating the geometry and system desing of the reactor, was erected at INET. The primary loop consists of two parallel vertical sections risers and steam separators, one heat exchanger, one steam condenser and down comer, throttle valves and conception tubes. The maximal power supply is 2×200 kW, the design pressure for the loop is 2.0 MPa, and the total height of the test system is about 7 m. Desalinated water is used as working fluid. It enters the heated section with the required subcooling, leaves its exit as steam-water mixture, and flows through the riser into the separator. The steam coming from the separator gets into the condenser, from where the corresponding condensate flows back into the liquid section of the separator. The saturated water flows from the separator through the heat exchanger, where it reaches the specified subcooling, through the throttle valve, which is used for setting the resistance coefficient, and through the main flowmeter, and then flows back through the channel throttle valves and channel flowmeters into the inlet of the two heated sections, thus closing the natural circulation. The system pressure and the inlet subcooling are adjusted by controlling the secondary mass flow through the condenser and the heat exchanger, respectively.

A series of experimental investigation have been performed with the help of the loop. It was observed that subcooled boiling and void flashing, which is caused by pressure drop in the riser, have a great influence on the flow instability of the natural circulation system. The void fraction caused by subcooled boiling in the heated section is very important for neutronic feedback in a low temperature heating reactor. The void fraction caused by void flashing in the adiabatic riser can increase the circulation mass flow rate. So it is necessary to obtain a realistic result for the distribution of the void fraction along the heated section and the riser. Recently theoretical interpretation of these experimental results has been initiated by a computer simulation, taking into account subcooled boiling in the heated section and void flashing in the riser.

The following studies are focused on the effect of subcooled boiling and of void flashing on the distribution of the void fraction and on the natural circulation flow, using a non-linear non-equilibrium hydrodynamic model.

1 ANALYTICAL APPROACH

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 it reaches finally saturation temperature due to gravity pressure drop, and void flashing begins at Z_F. The computer simulation rests on a one-dimensional two-phase flow drift model with the following conservation equations for mass, steam, energy, and momentum.

Mass conservation:

$$\frac{\partial}{\partial t}[(1-\varepsilon)\rho_F+\varepsilon\rho_D]+\frac{\partial}{\partial z}[(1-\varepsilon)\rho_F w_F+\varepsilon\rho_D w_D]=0 \quad (1)$$

steam conservation:

$$\frac{\partial}{\partial t}(\varepsilon\rho_D)+\frac{\partial}{\partial z}(\varepsilon\rho_D w_D)=\frac{Uq\psi}{Ar}-\frac{Q_c}{Ar}\text{[2]} \quad (2)$$

energy conservation:

$$\frac{Uq}{A}=\frac{\partial}{\partial t}[(1-\varepsilon)\rho_F h_F+\varepsilon\rho_D h_D]+\frac{\partial}{\partial z}[(1-\varepsilon)\rho_F w_F h_F+\varepsilon\rho_D w_D h_D] \quad (3)$$

momentum conservation:

$$\frac{\partial}{\partial t}[(1-\varepsilon)\rho_F w_F+\varepsilon\rho_D w_D]+\frac{\partial}{\partial z}[(1-\varepsilon)\rho_F w_F^2+\varepsilon\rho_D w_D^2]=$$

$$-\left(\frac{\partial p}{\partial z}\right)+\left(\frac{\partial p}{\partial z}\right)_l+\left(\frac{\partial p}{\partial z}\right)_f+\left(\frac{\partial p}{\partial z}\right)_g \tag{4}$$

To solve these equations, the following correlation[2,3] are needed:

$$(1-\varepsilon)w_F=\left(\frac{1}{C_0}-\varepsilon\right)w_D-\frac{V_{dj}}{C_0} \tag{5}$$

$$\psi=\frac{(T_w-T_s)^2}{(T_w-T)^2} \tag{6}$$

$$Q_c=\frac{3A\varepsilon q}{R_B}\frac{(T_S-T)^2}{(T_W-T)^2-(T_W-T_S)^2} \tag{7}$$

$$\rho_F=\rho_F(p,T),\rho_D=\rho_D(p,T_s(p)),h_D=h_D(p,T_s(p))$$

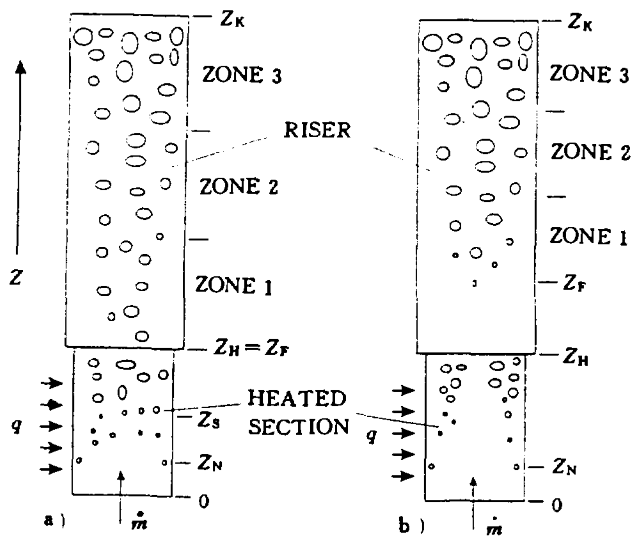

Fig. 1 Two-phase flow pattern in the test loop

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 $Z_F>Z_H$.

The investigated system consists of a subcocled single-phase region, a subcooled boiling region, a bulk boiling region in the heated section, a two-phase region in the adiabatic riser, which is divided into smaller sections in order to calculate void flashing exactly, and a single-phase region in the subcooler and down-comer. To solve the equations by an integration method, it is necessary to convert them into suitable forms.

1.1 Equations for the Heated Section

From Eqs. (1), (2) and (3) we obtain the equation for the enthalpy of water:

$$\frac{\partial}{\partial t}[(1-\varepsilon)\rho_F h_F] + \frac{\partial}{\partial z}[(1-\varepsilon)\rho_F w_F h_F] = UqA^{-1}\left(1-\psi\frac{h_D}{r}\right)^{-1} + \frac{Q_c}{A}\frac{h_D}{r} \quad (8)$$

From Eqs. (1) and (5) we get the equation for the void fraction:

$$\frac{\partial}{\partial t}\varepsilon + \frac{\partial}{\partial z}\varepsilon w_D = \frac{\rho_F}{C_0\rho_{FD}}\frac{\partial}{\partial z}w_D \quad (9)$$

The equation for the steam velocity can be derived form Eqs. (2) and (5):

$$\frac{\partial}{\partial z}w_D = \frac{C_0\rho_{FD}}{\rho_F\rho_D Ar}(Uq\psi - Q_c) \quad (10)$$

1.2 Equations for the Adiabatic Riser

From Eqs. (1) and (3) we get the equation for void fractions:

$$\frac{\partial}{\partial t}(\varepsilon\rho_D) + \frac{\partial}{\partial z}(\varepsilon\rho_D w_D) = -\frac{1}{r}\left[\rho_F(1-\varepsilon)\frac{\mathrm{D}h_{Fs}}{\mathrm{D}t} + \varepsilon\rho_D\frac{\mathrm{D}h_{Ds}}{\mathrm{D}t}\right] \quad (11)$$

with

$$\frac{\mathrm{D}h_{Fs}}{\mathrm{D}t} = \frac{\partial}{\partial t}h_{Fs} + w_F\frac{\partial}{\partial z}h_{Fs}, \quad \frac{\mathrm{D}h_{Ds}}{\mathrm{D}t} = \frac{\partial}{\partial t}h_{Ds} + w_D\frac{\partial}{\partial z}h_{Ds}$$

$$\frac{\partial}{\partial z}h_{Fs} = \frac{\partial}{\partial p}h_{Fs}\frac{\partial}{\partial z}p, \qquad \frac{\partial}{\partial z}h_{Ds} = \frac{\partial}{\partial p}h_{Ds}\frac{\partial}{\partial z}p$$

$$\frac{\partial p}{\partial z} = -[(1-\varepsilon)\rho_F + \varepsilon\rho_D]g \quad (12)$$

From Eqs. (9) and (11) we obtain the equation for the steam velocity:

$$\frac{\partial}{\partial z}w_D = \frac{C_0\rho_{FD}}{r\rho_F\rho_D}\left[\rho_F(1-\varepsilon)w_F\frac{\partial}{\partial p}h_{Fs} + \varepsilon\rho_D\frac{\partial}{\partial p}h_{Ds}\right]\left(-\frac{\partial}{\partial z}p\right) \quad (13)$$

for the flashing front we use the Clausius-Clapeyron equation:

$$\frac{\mathrm{d}p}{\mathrm{d}T} = \frac{1000r}{T}\frac{\rho_F\rho_D}{(\rho_F-\rho_D)} \quad (14)$$

Through integration of Eq. (8) from $Z=0$ to $Z=Z_N$ and from $Z=Z_N$ to $Z=Z_S$, and of Eq. (14) from $Z=Z_F$ to $Z=Z_K$, time dependent parameters, viz., the subcooled boiling front (Z_N), the bulk boiling front (Z_S), and the flashing front (Z_F) are determined. Time dependent average void fractions in each region are obtained through integration of Eqs. (9) and (11) in each corresponding region. Velocities in needed positions can be obtained by integration of Eqs. (10) and (13). Finally, the relationship of various parameters can be determined by integration of momentum equation (4) over the closed loop. Thereby we achieve a system of ordinary differential equations which simulate the thermohydraulic behavior of the natural circulation loop. The group of equations is solved by the Runge-Kutta-Verner 5th and 6th order method. Describing the time dependence of only a few local parameters in each region is sufficient to get a general physical understanding of the natural circulation in the loop and saves computing time.

2 RESULTS FOR STEADY STATE

Fig. 2 shows the mass flow rate, obtained from experiment and two different calculation models NCBF and N0B0, as a function of the heat flux. NCBF is a model which considers subcooled boiling, bulk boiling in the heated section, and void flashing in the adiabatic riser, while N0B0 only takes account of bulk boiling in the heated section. It can be seen that both models predict the experimental mass flow rate well under a system pressure of 1.5 MPa, and that in the low heat flux region the agreement with experimental data is better in the case of NCBF. The designed operating heat flux for the 5 MW heating reactor is abut 200 kW/m^2. So NCBF should be used in practical analysis.

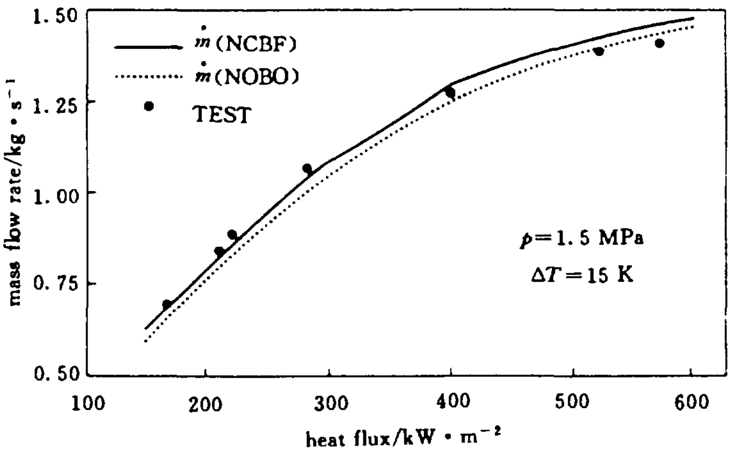

Fig. 2 Mass flow rate in the test loop HRTL-5

Other parameters predicted by the two models, such as void fraction, water temperature, boiling fronts, etc., show obvious differences. These differences have a strong effect on the dynamic behavior. Fig. 3 presents the distribution of the void fraction along the heated section and the riser. In N0B0, bulk boiling occurs at the end of the heated section, between a bulk boiling front (Z_S=0. 53 m) and the end of the heated section (Z_S=0. 58 m). At the inlet of the riser the void fraction decreases due to the increased flow area, then it remains unchanged up to the end of the riset. In NCBF, subcooled boiling occurs much earlier in the heated section, between the subcooled boiling front (Z_N=0. 25 m) and Z_H. There is no bulk boiling in the heated section, because the water temperature does not reach the saturated temperature at the end of the heated section. The void fraction at the inlet of the riser decreases due to the increased flow area and the condensation of subcooled bubbles coming from the heated section. After part of the subcooled bubbles condense, the water at the inlet of the riser reaches its saturated temperature, and thermal equilibrium is reached at this position. In riser the void fraction increases because of void flashing. The flashing process can be explained as follows. As the fluid is flowing up, the static pressure decreases due to friction, acceleration and, mainly, gravity pressure drop. Therefore, water and steam are overheated, and the difference of the two saturated enthalpies of water and steam between the corresponding two points is released. The released energy evaporates part of the water. So the void fraction increases along the adiabatic riser. By the way, void flashing is a quasi thermal-equilibrium process. Two experimental points representing void flashing in the riser are given in Fig. 3. Flashing is well predicted by NCBF.

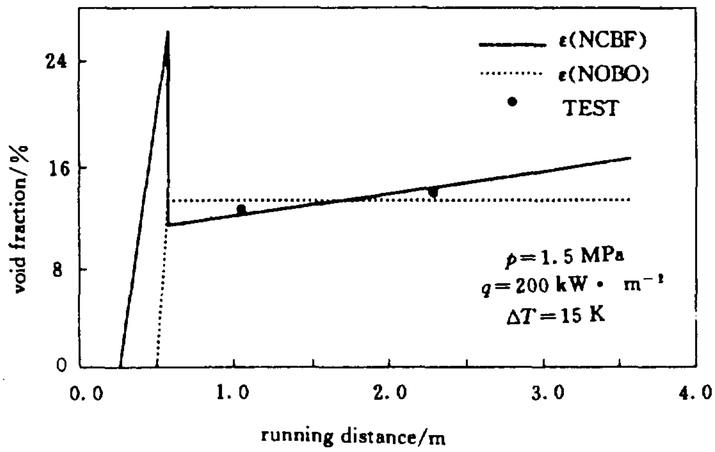

Fig. 3 Distribution of the void fraction in heated section and riser as predicted by the two models

Fig. 4 shows the temperature T_H and the saturation temperature T_{Hs} of the water at the exit of heated section Z_H, and the mixture temperature T_m at the inlet of riser, in dependence the inlet subcooling at $Z=0$. The mixing temperature is defined as

$$T_M = \frac{w_{FH}\rho_{FH}(1-\varepsilon)h_{FH} + w_{DH}\rho_{DH}\varepsilon_H h_{DH}}{c_p G} \tag{15}$$

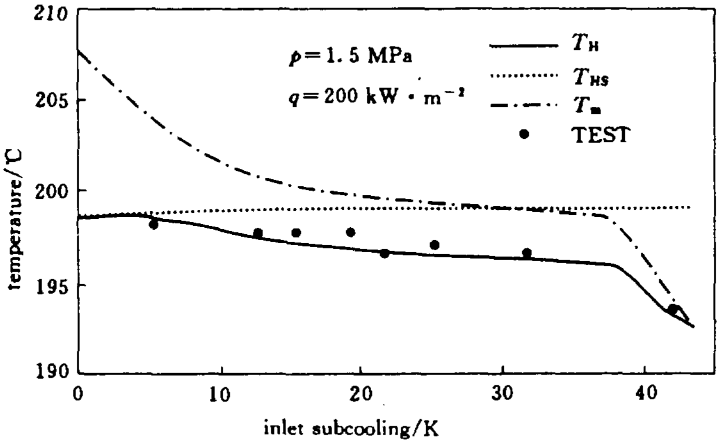

Fig. 4 Temperature at the exit of the heated section and at the inlet of the riser

It is the fictive maximal water temperature which would be reached if all the steam were condense. If T_m is greater than T_{Hs}, equilibrium will be reached by condensation of the non-equilibrium bubbles from the heated section, and there will be a void fraction at the inlet of the riser. The greater the difference T_m and T_{Hs}, the greater the void fraction will be. If T_m is smaller than T_{Hs}, there will be no void fraction at the inlet of the riser, the void in the upper part of the riser is then purely caused by flashing. When the inlet subcooling is small, T_H equals T_{Hs}, which means that there is bulk boiling in the heated section. In a wide range of medium inlet subcooling, T_H is smaller than T_{Hs}, and T_m greater than T_{Hs}, which means that there is subcooled boiling only in the heated section, and the non-equilibrium bubbles from the heated section are partly condensed, and equilibrium bubbles exist in the inlet of the riser. When the inlet subcooling is large, T_H and T_m are below the saturation temperature T_{Hs}, which means that subcooled boiling occurs in the heated section and flashing begins not at the inlet but at the flashing front Z_F of the riser. After T_H has reached T_m, all types of boiling disappear. The saturation temperature at the exit of the riser is T_{k0} = 198. 3℃, and the maximal temperature T_{Hs} = 199. 0℃. The difference (ΔT_{Hks}) between T_{Hs} and T_{k0} is a measure for the flashing ability. The difference $\Delta h_{HK} = c_p \Delta T_{Hks}$ of the saturation enthalpies of water between inlet and exit of the riser will determine the conversion of a part of the water into steam.

Fig. 5 shows the void fraction at inlet and exit of the riser in dependence on the inlet subcooling. The difference between ε_{K3} and ε_K is the flashing void fraction. For small ΔT, the flashing void fraction is small, because, firstly, in this case T_{Hs}, namely ΔT_{Hks} is low (see Fig. 4) and so the flashing ability is poor, secondly, the absolute value ε_K is high in this region, so the same amount of flashed steam quality brings less increase of void fraction. At high ΔT, subcooled boiling begins very late, and there is no bulk boiling in the heated section. The non-equilibrium void is fully condensed at the inlet of the riser. The water temperature at the inlet of riser does not reach its saturation value after the condensation of subcooled bubbles. As the water flows up, a point (flashing front) Z_F is reached at which the water reaches its saturation temperature, and void flashing begins. The flashing void fraction reaches its maximal value when ε_K becomes zero and pure flashing begins in the riser. Then the flashing void fraction decreases, because the flashing span becomes small. The saturation temperature at the exit of the riser is T_{k0}=170. 4℃, and the maximal temperature T_{Hs}=171. 8℃, so that the flashing ability is about two times greater than at 1. 5 MPa. The calculates for a system pressure of 1. 5 MPa are similar to those obtained at 0. 8 MPa. But subcooled boiling in the heated section and flashing in the riser are not so intense as 0. 8 MPa.

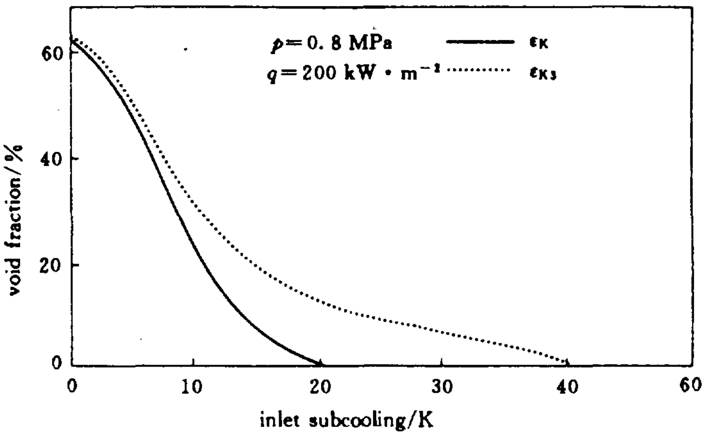

Fig. 5 Void fraction at inlet and exit of the riser

3 RESULTS FOR DYNAMIC

Based on the results for steady state, the behavior of dynamic of the 5 MW heating reactor is investigated. The mechanism of flow oscillation is described as the following: 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 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 of suitable phase lags. Fig. 6 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, T_S: saturation temperature, T_E: liquid temperature at $Z=0$. For subcoolings in the range $0\leqslant T_S-T_E<14.6$ K a stable two-phase flow exists in the test loop at system pressure of 1.5 MPa and a heat flux of 200 kW/m^2.

Correspondingly, at a subcooling of 14.0 K the oscillation amplitudes decay. The amplitude ratio of consecutive oscillations, the decay ratio Y_{i+1}/Y_i (Fig. 6), is a measure of the flow stability. If the inlet subcooling is increased to 14.6 K the decay ratio approaches 1. 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 of the inlet subcooling from 14.6 K to 14.8 K results in an increase of the oscillation amplitude from 3% to 11% (Fig. 6). At high subcoolings 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 $T_S-T_E=26$ K. The analysis shows that for the instability range of $14.6\text{ K}<T_S-T_E<26$ K only non-equilibrium boiling occurs in the heated section; the saturation temperature is never reached at Z_H. The increase of the volumetric steam fraction by void flashing can be traced in Fig. 7 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. The analysis of one-and two-phase flow pressure drop changes close to the lower and upper stability boundary confirms that self-sustained oscillations are related to a 180 degree lag, Fig. 8. In spite of great differences in the absolute one- and two-phase pressure losses ($\Delta p_{1ph}=3360$ Pa, $\Delta p_{2ph}=22837$ Pa), the amplitudes of the pressure drop oscillations are nearly equal. They oscillate in counter-phase, the absolute change of the total pressure drop during the mass flow oscillations is close to zero. This "zero-pressure-drop" is the main cause for the instability.

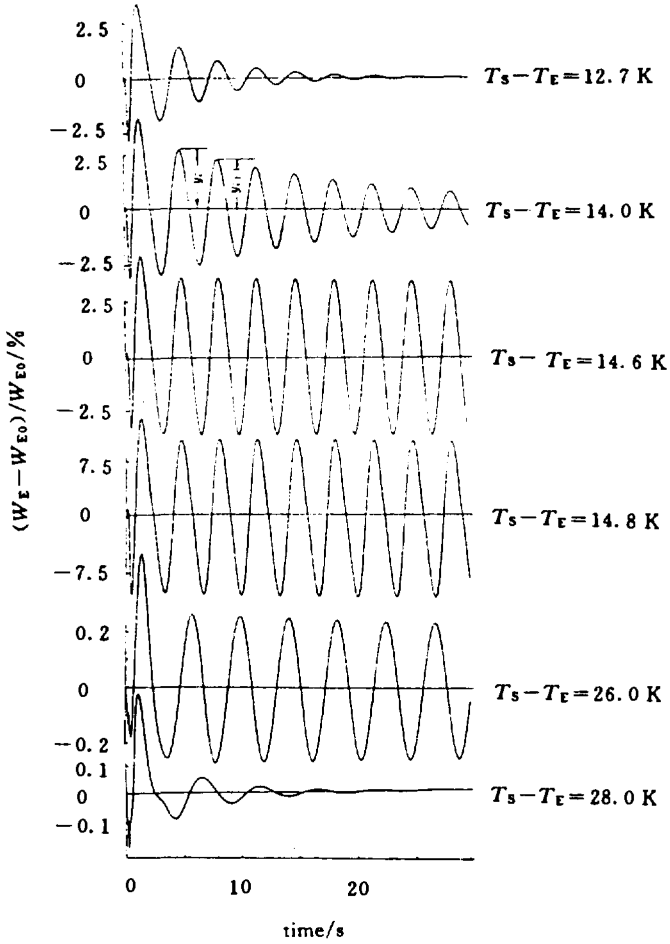

Fig. 6 Relative oscillation amplitudes of the inlet velocity w_E for different inlet subcoolings

$p=1.5$ MPa, $q=1$ kW/m²

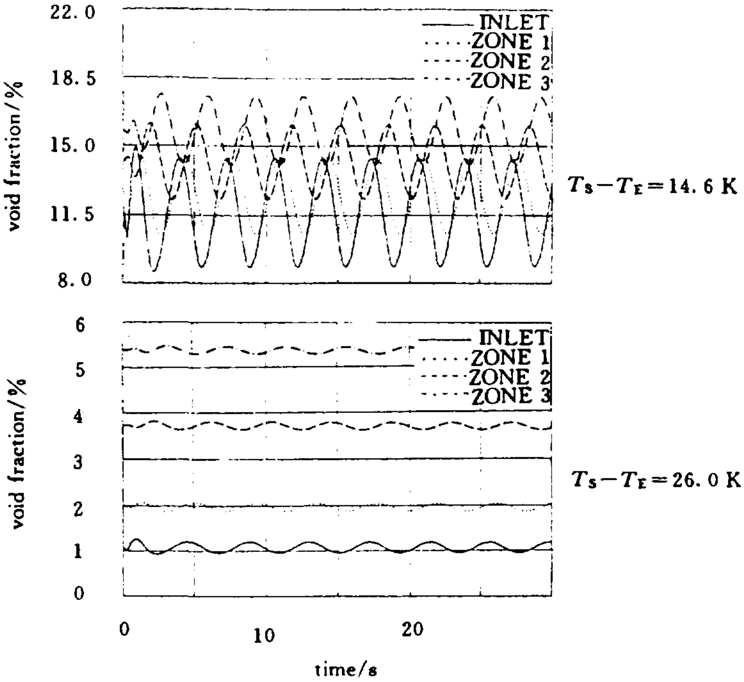

Fig. 7 Void fraction in three sub-zones of the riser, close to the lower and upper stability boundary
$p=1.5$ MPa, $q=1$ kW/m²

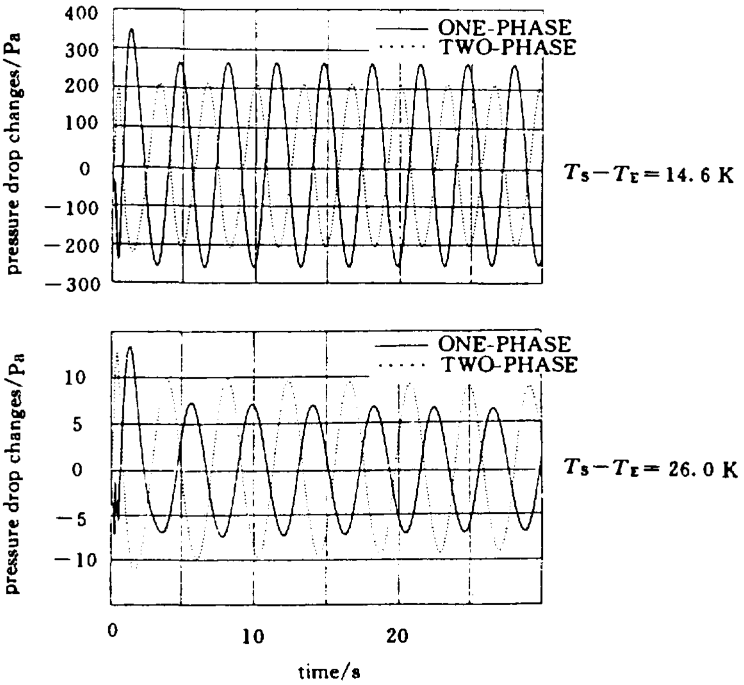

Fig. 8 Pressure drop changes in the one-and two-phase regions, close to the lower and upper stability boundary
$p=1.5$ MPa, $q=1$ kW/m²

The main control parameters of a heating reactor with natural circulation are power and subcooling. Therefore, experimental and theoretical data on flow instability are provided in power-subcooling stability maps. Fig. 9 displays the calculated stability map of the INET test loop HTRL-5 at a system pressure of 1.5 MPa, and six results of experimental tests for comparison. In accordance with the oscillation phenomena in Fig. 6 (at a heat flux of 200 kW/m^2), there are two stability boundaries, dividing the (heat flux, subcooling) stability map in three regions: The stable single-phase and deep subcooled boiling flow region A, the unstable two-phase flow region B, characterized by coupled flashing-density wave oscillations, and the stable two-phase flow region C. The upper boundary limits essentially the single-phase operation of a heating reactor, the lower boundary limits the two-phase operation.

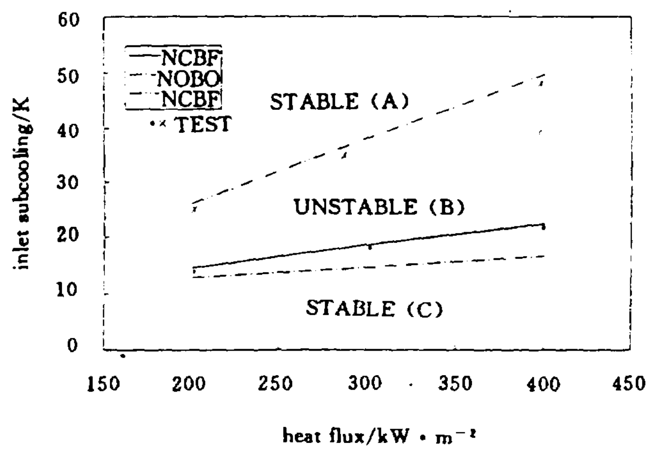

Fig. 9 Stability map of the test loop HRTL-5

p=1.5 MPa

The two calculating models NCBF and N0B0 have been applied to evaluate the lower stability boundary. Fig. 9 indices that NCBF is in better agreement with experiment than N0B0. The upper stability boundary in the deep subcooled boiling flow region can be predicted by NCBF only.

4 CONCLUSION

At low steam quality and low system pressure, natural circulation is dominated by non-equilibrium boiling and void flashing. A calculating model has been developed to study the thermohydraulic characteristic of nuclear heating reactor, and the mechanism of self-sustained flow oscillations in this regime.

The flashing ability increases with increasing length of the riser, and decreases with increasing system pressure. For a system with short heated section, long riser and low pressure, there is almost no void fraction in the heated section, but a large void fraction is in the riser. So the mass flow rate can be rather high. Evaluated stability boundaries for the INET test loop HTRL-5 can be verified in good agreement with experimental test results.

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LIST OF SYMBOL

A flow area

C_0 distribution parameter in Drift-Model

c_p specific heat capacity at constant pressure

G mass flux

g acceleration of gravity

h specific enthalpy

p pressure

q heat flux

Q_c heat condensed from subcooled vapor to water (W/m)

R_B radius of subcooled steam bubble

r latent heat

T temperature (℃)

ΔT inlet subcooling ($T_s - T_E$)

t time

U perimeter of heated rods

V_{dj} relative velocity in Drift-Model

w velocity

z running distance above inlet of heated section

ψ fraction of heat-generated vapor at surface of heated rod

ρ density

SUBSCRIPTS

D vapor

F water of flashing front
FD difference between vapor and water properties
f resistance
g gravity
H exit position of heated section
HK difference between inlet and exit of riser
K riser
Ki subsection i of riser
l local
m mixing
N net vapor generating point (subcooled boiling front)
S bulk boiling front
s saturated condition
W wall of heated rods

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