Inlet steam quality of a top break hole on horizontal pipe*

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Abstract The inlet steam quality of the top break on horizontal pipe was investigated on the high pressure steam-water two-phase loop of Xi'an Jiaotong University using the γ-ray attenuation technique. The mass attenuation coefficient of the γ-ray penetrating high pressure saturated water was measured, and it is shown that such a coefficient nearly keeps constant. The correlation of the inlet steam quality to the dimensionless number h/h_b was obtained. The experimental results also indicate that the break inlet pressure was reduced due to the Bernoulli effect induced by the two-phase mixture advancing into the break. Such a pressure loss was verified to be an important and sensitive parameter to determine the critical discharge mass flow rate.

Keywords: *horizontal pipe, stratified flow, steam quality.*

The small break loss-of-coolant accident of water cooled nuclear reactor has captured much attention since the Three-Mile Island Accident of America. If the break is located at the horizontal hot leg or cold leg, the circulation mass flow rate of RCS (reactor core system) is low because the circulation pump does not work, and the stratified flow may take place in the horizontal pipe. Under this condition, the break orientation (top branch, side branch or bottom branch) may apparently affect the discharge mass flow rate through the break[1]. The available thermal hydraulic analysis codes, such as RELAP5/MOD2 and TRAC-PF1, which are the experimental correlations conducted on the low-pressure air-water loop were used to calculate the steam quality and discharge mass, but the prediction results cannot match well with the experimental data of system transient[2, 3].

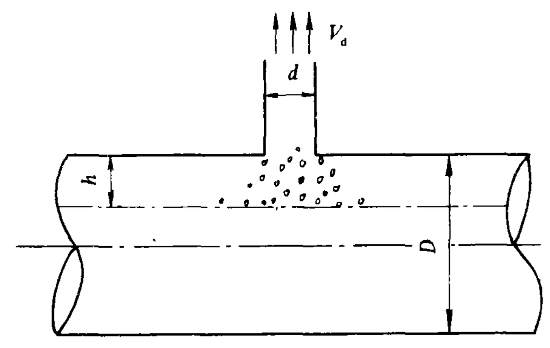

Fig. 1. Small top break with horizontal pipe.

As shown in fig. 1, the inner diameter of horizontal pipe is D, the break diameter is d, the elevation difference between bulk water level and break is h. There is a critical height h_b at

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which the liquid begins to be entrained. When $h>h_b$, the single-phase vapour flows through the break, and the liquid at the stratified interface cannot be entrained; when $h=h_b$, the liquid begins to be entrained, but the break inlet steam quality $x_{b,i}$ is equal to zero; when $h<h_b$, the liquid at the interface is pulled through by the vapour to the break, and $x_{b,i}>0$. The objective of the present report is to determine $x_{b,i}$ when $h<h_b$.

Once the break inlet quality and break inlet pressure are determined, the discharge mass flow rate through break can be acquired based on the available critical flow model; therefore we should obtain h_b at first.

1 Onset of liquid entrainment

The ratio of critical height h_b at which the interface liquid begins to be entrained to the break diameter d during discharge from top break on horizontal pipe can be correlated as

$$\frac{h_b}{d}=A\cdot Fr^B, \tag{1}$$

where A and B are constants which could be determined by experiment or theoretical analysis. Fr is the Frouder number given by

$$Fr=\frac{V_d}{\sqrt{gd\frac{\Delta\rho}{\rho}}}, \tag{2}$$

$$V_d=\frac{W}{\frac{1}{4}\pi d^2\rho}, \tag{3}$$

where g is the gravitational acceleration, ρ is the density of the vapour, $\Delta\rho$ is the density difference between steam and water, W is the mass flow rate through the orifice and V_d is the mean discharge velocity

The present paper uses the correlation of $h_b/d=1.67Fr^{0.4}$ performed in ref. [4] to predict the critical height at the onset of the liquid entrainment.

2 Experiment

The experiment was conducted in Xi'an Jiaotong Universtiy. As shown in fig. 2(a), the feedwater is pressurized by a plunger pump and separated into two circuits: one is the bypass to adjust the mass flow rate, and the other flows through two orifices, a regenerative heat exchanger and then into an inclined heated section. The fluid in the inclined tube is heated by the A. C. power, and the total heat supply is up to 450 kW. The outer surface of the heated tube is also well insulated. The fluid flows out of the heated tube, enters the pressure vessel, then goes to the horizontal circular test section from the left side as well as the right side with 3.0 m horizontal steady section for each side. The

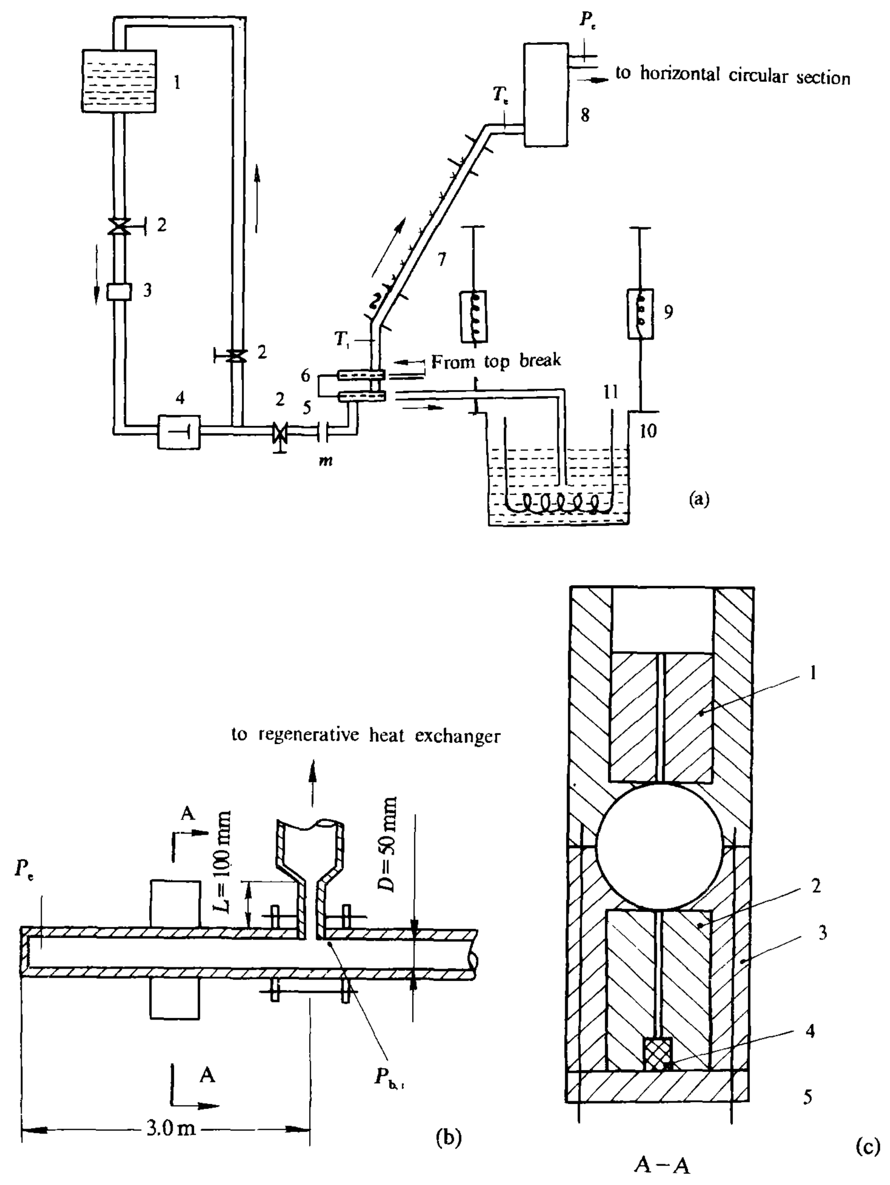

Fig. 2. (a) Test facility of experiment. 1, Water tank; 2, control valve; 3, filter; 4, high pressure plunger pump; 5, orifice, 6, regenerative heat exchanger; 7, inclined heated section; 8, pressure vessel; 9, load cell; 10, water tank; 11, copper-made heat exchanger. (b) Horizontal circular section. (c) γ-ray detector. 1, Collimation B; 2, collimation A; 3, aluminum case; 4, ^{137}Cs source; 5, regular screw.

break is simulated with a sharp-edged tube with the inner diameter of 4.0 mm. One of the three break orientations (upward, sideward and downward) can be selected for a test by putting the break simulation duct in each direction. The fluid temperature T_i was measured with a jacket thermocouple at the inlet of the heated section, and another jacket thermocouple was also installed for recording the fluid temperature at the outlet of the heated section. The upstream bulk pressure P_e was detected by an absoulte pressure transducer, and another pressure transducer was arranged at the inlet of the break to obtain the pressure $P_{b,i}$. All electric signals were transformed into an IBM386 computer through the IMP3595C data collector.

The liquid level in the main horizontal pipe was measured by the γ-ray attenuation monitor which mainly includes γ-ray source, collimation A, absorption collimation B, scintillation crystal detector and scintillation counts. The γ-ray beam has the source intensity of 30 mC, half decay life of 29.9 a and energy of 0.662 MeV. The objective of using collimation is to form narrow beam so as to eliminate scattering and annihilate γ radiation (see figure 2(c)).

The linear attenuation coefficient of water at the ambient pressure and the temperature was recorded to be $0.086\,\mathrm{cm}^{-1}$; however, for high pressure and temperature water, the linear attenuation coefficient is different from that at the ambient pressure and temperature. When high pressure saturated water was contained in the horizontal pipe, the following equation can be used to determine the linear attenuation coefficient μ.

$$I = I_0 \exp\left(-\frac{\mu}{\rho}\rho D\right), \tag{4}$$

where I_0 is the counts per minute when the horizontal pipe was vacuum, I is the counts per minute when saturated water was included in the tube, ρ is the density of saturated water, and D is the inner diameter of the horizontal pipe. Both the linear attenuation coefficient μ and the mass attenuation coefficient μ/ρ are plotted in fig. 3. It is seen that the mass attenuation coefficient μ/ρ keeps nearly constant, even though the linear attenuation coefficients vary with the fluid pressure.

With stratified co-current two-phase flow in the horizontal pipe, the liquid level h_l in the main pipe can be predicted according to

$$I' = I_0 \exp\left(-\frac{\mu}{\rho}\rho h_l\right), \tag{5}$$

where I' is the counts per minute with stratified flow occurring in the main pipe; therefore the elevation difference between the bulk water level and break is $h = D - h_l$; μ/ρ is determined based on figure 3.

It should be noted that in thermal hydraulic codes, the liquid level in the main pipe during small break loss-of-coolant accident was obtained by solving the thermal hydraulic equations.

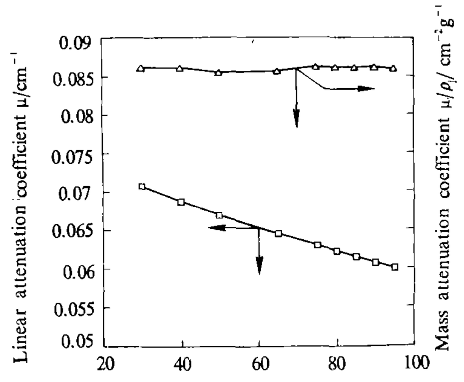

Fig. 3. γ-ray attenuation coefficient versus pressure.

The next step is to determine the heat absorption efficiency of the inclined heated section. When the main circuit was operating for enough time so as to ensure the main circuit to reach the steady equilibrium state, the heat absorption efficiency can be acquired by

$$\eta Q = \eta \sum_{i=1}^{6} Q_i = m(i_e - i_i), \tag{6}$$

where m is the mass flow rate of the heated tube, i_e and i_i are enthalpies at corresponding temperature T_e and T_i. Q_i is calculated using the measured values of large capacity voltage transmitter and current transmitter. With two-phase mixture flowing in the inclined tube, the exit enthalpy of the heated pipe is

$$i_e = i_i + \frac{\eta \sum_{i=1}^{6} Q_i}{m}. \tag{7}$$

The corresponding steam quality is

$$x_e = \frac{i_e - i_l}{i_g - i_l}, \tag{8}$$

where i_g and i_l are saturated enthalpies of vapor and liquid. For insulated horizontal circular tube, based on the principle of mass and energy conservation, the break inlet steam quality should be equal to the exit vapor quality of the inclined heated tube, i.e.

$$x_{b,i} = x_e. \tag{9}$$

However, the vapor accelerates and entrains the liquid to the break in the break entrance region, the saturated liquid flashing may take place during such a liquid entrainment process, which makes the break inlet vapor quality larger than x_e. The break inlet enthalpy $i_{b,i}$ can be assumed to be equal to the exit enthalpy of the inclined heated pipe. From

$$i_{b,i} = i_e = i_g x_{b,i} + i_l(1 - x_{b,i}), \tag{10}$$

we obtain

$$x_{b,i} = \frac{i_e - i_l}{i_g - i_l}. \tag{11}$$

Great attention should be paid to the fact that i_g and i_l are determined by pressure $P_{b,i}$.

After the above work has been done, detailed steam quality experiment was performed. Fig. 4 illustrates the break inlet vapor quality $x_{b,i}$ versus the dimensionless number h/h_b, while $x_{b,i}$ was calculated by exit enthalpy of the heated inclined tube and break inlet pressure $P_{b,i}$. Fig. 4 shows that with the increasing elevation difference between the bulk water level and break h, the inlet vapor quality is increased, while the corresponding critical mass flow rate is decreased. The limited condition is that when $h/h_b = 1$, $x_{b,i}$ reaches unity; that is to say, the break inlet does not contain liquid under this condition. From fig. 4, we also know that the break inlet pressure does not apparently affect the vapor quality, and the break inlet vapor quality can be correlated as

$$x_{b,i}=1.07c^{3.25(1-c)^2}, \tag{12}$$

where c is equal to h/h_b, and the discrepancy relative to the mean value of the experimental results is not greater than 11.2%.

From the experiment, we also know that the break inlet pressure was apparently decreased due to Bernoulli effect caused by the vapor acceleration and entraining the liquid to the break in break entrance region. The pressure loss which does not depend upon the

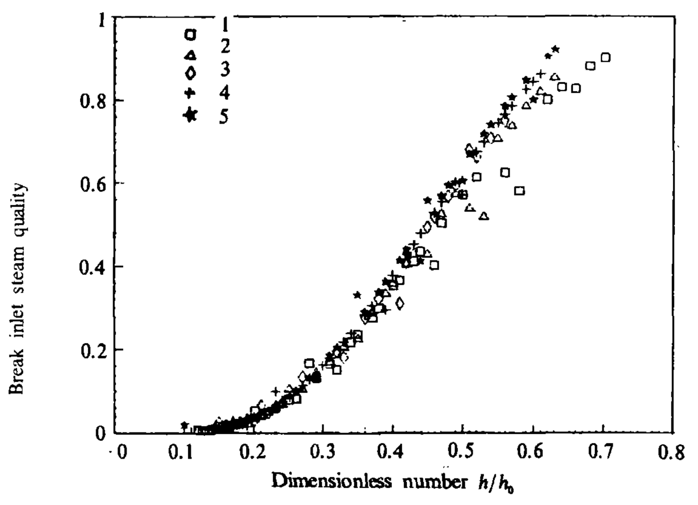

Fig. 4. Break inlet steam quality versus dimensionless number h/h_b. □, $P_{b,i}=(3.5\pm0.04)$ MPa; △, $P_{b,i}=(5.0\pm0.04)$ MPa; +, $P_{b,i}=(6.5\pm0.03)$ MPa; ★, $P_{b,i}=(9.5\pm0.04)$ MPa.

liquid level in the main pipe obtains a certain value at given upstream bulk pressure (see fig. 5), and can be correlated as

$$P_e-P_{b,i}=-15.09+5.346\log_e P_e, \tag{13}$$

where the unit of pressure is bar.

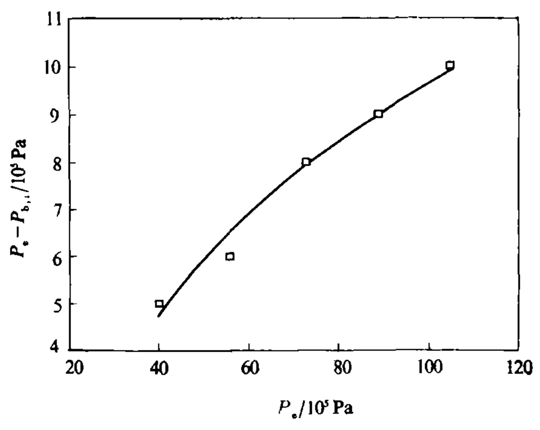

Fig. 5. Pressure loss $P_e-P_{b,i}$ versus upstream bulk pressure.

Figure 6 presents a comparison of the meausred critical mass flow rates with the estimated values calculated by the upstream bulk pressure and the exit enthalpy of the heated section. The calculated mass flow rates were always larger than the measured values, under the assumption that there is no difference between the upstream bulk pressure and the break inlet pressure. The consistence can be found in fig. 7 between

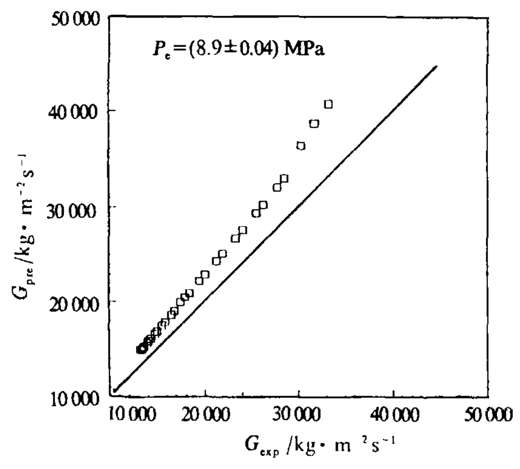

Fig. 6. Comparison of the critical mass flow rate calculated based on upstream bulk pressure and exit enthalpy of heated section with measured values.

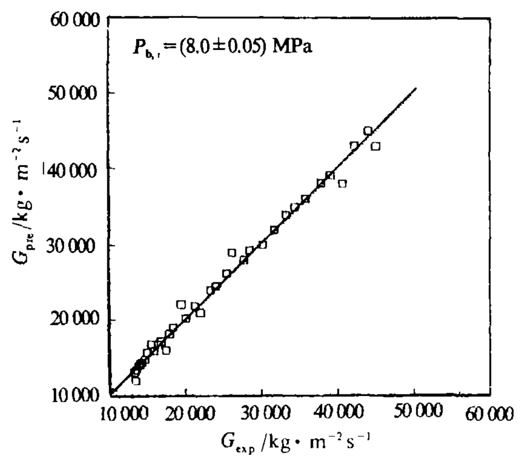

Fig. 7. Comparison of critical mass flow rate calculated based on break inlet pressure and break inlet steam quality with measured values.

the measured critical mass flow rates and the values estimated by measuring break inlet pressure and the break inlet steam quality.

3 Conclusions

(1) The present work performed the break inlet steam quality experiment under the condition of horizontal pipe small top break of pressurized water reactor for the first time.

(2) The mass attenuation coefficient of γ-ray penetrating high pressure saturated water was verified to be constant by experiment.

(3) The break inlet steam quality is mainly dependent on the dimensionless value h/h_b.

(4) The break inlet pressure was apparently reduced due to Bernoulli effect exerted by the two-phase mixture acceleration in break entrance region. This pressure loss was also a sensitive parameter to predict the critical mass flow rate.

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