Experimental investigation on jet breakup behavior in the lower plenum of a boiling water reactor under isothermal conditions

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Abstract：In a hypothetical severe accident, the fuel assemblies and structure in the core region could melt. The corium from the core region may fall into the reactor lower plenum. Jet breakup phenomenon would happen while corium falling into water pool in the lower plenum. In a boiling water reactor lower plenum, the control rod guide tubes (CRGTs) will create flow channels for the falling jet. Therefore corium jet breakup behavior could be affected by these CRGTs. Thus, it is important to investigate CRGTs effect on the jet breakup behavior. In order to investigate CRGTs effect on the jet breakup behavior, a molten material (U-alloy) breakup experiment was conducted under isothermal condition. The experiment results indict that CRGTs restrain the jet breakup process. For the case with CRGTs pitch/diameter ratio of 1.37, the jet breakup fraction was approximately 20% of that for the case without CRGTs. The test was also conducted for the case with a coarser pitch/diameter ratio of 2.47, but the amount of jet breakup was only slightly reduced in this configuration. The experiments also indict that the departure droplets diameter was almost not affected by CRGTs. Furthermore, the particle image velocimetry (PIV) method was used to measure water velocity distribution around the jet. The water velocities surrounding the jet for the case without CRGTs were smaller than those in the case with CRGTs.

Keywords: BWR lower plenum, jet breakup, severe accident, isothermal condition

1. Introduction

In a hypothetical severe accident, molten core material could fall into water pool in the reactor lower plenum with jet breakup process[1]. There are many control rod guide tubes (CRGTs) and instrument guide tubes (IGTs) in the lower plenum of boiling water reactor (BWR). The CRGTs in BWRs will create flow channels for the falling jet. Thus, it is important to investigate the influence of CRGTs on the jet breakup process.

Such experiments have been performed by Saito et al.[2] and the results indicated that CRGTs could prevent jet expanding in the radial direction. In order to visualize jet breakup behavior, Fluorinert was used to simulate molten core material in Saito et al.'s experiments. However, this experiment did not give the jet breakup fraction. The surface tension of Fluorinert is similar to water, which may reduce droplet departure from the surface of the jet.

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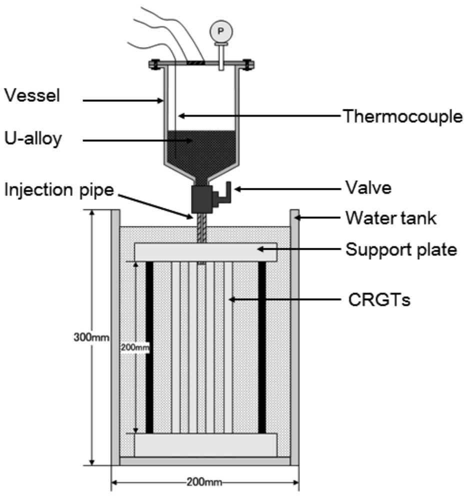
In the present study, U-alloy 48 (composition of Bi, Pb, Sn, Cd, and In) is chosen to simulate molten core material by considering the physical properties and conducting the experiment under isothermal conditions. Such kinds of lower melt point alloys have widely been used in jet breakup studies by other researchers, such as Abe et al. [3] and Bang et al. [4].

The present work is experimental investigation of CRGTs effect on the breakup of a molten metal jet in the lower plenum of BWR under isothermal conditions. A high speed camera was used to capture the jet breakup behavior and the water velocity distribution surrounding the jet was measured by particle image velocimetry (PIV) method.

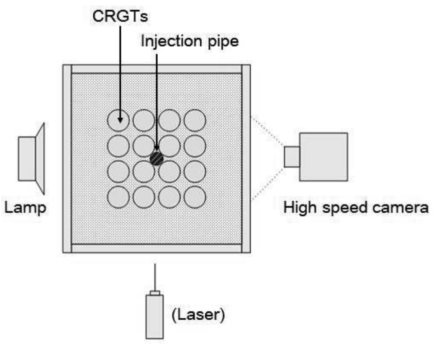
2 . Experimental apparatus

As shown in Figure 1, the experimental apparatus consists of a jet injection vessel, a test section, and measurement equipment. The jet injection vessel is made from stainless steel and covered with a stainless steel plate. The vessel and injection pipe were connected by a valve. During the experiment, in order to achieve a constant jet injection velocity, the vessel was pressured. An electrical wire was used to heat the U-alloy to the desired value. The water tank is made of transparent acrylic glass for visualization purpose. The lamp and high-speed camera were set at opposite side of the water tank, while the laser was set at the side of the water tank. Two illumination methods were used in this experiment. For the purpose of capturing the shapes of the jet and droplets, only lamp was used. While for the purpose of measuring water velocity distribution surrounding the jet, only laser was used.

The jet breakup behavior located behind the tubes could be captured, because the CRGTs were made from fluorinated ethylene propylene (FEP), of which the refractive index is similar to water. The pitch/diameter ratios (P/D) of the tubes are different in different regions of the BWR lower plenum. Based on the BWR lower plenum geometry, two test sections were chosen to study the jet breakup behavior in different regions of the BWR lower plenum. The pitch of the FEP tubes was varied (1.25 cm and 2.25 cm, separately) and the corresponding P/D values were 1.37 and 2.47, respectively.



(a) Front view



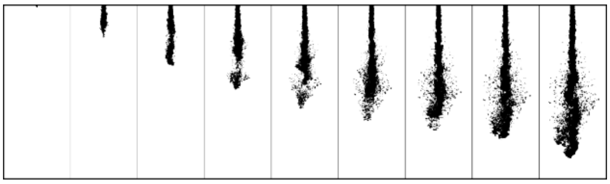
(b)Top view

Fig. 1 Schematic of the experimental facility (a) Front view (b) Top view

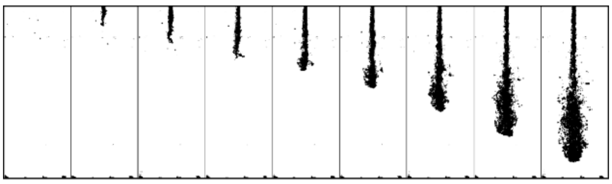
3. result and discussion

3.1 Jet injection behavior

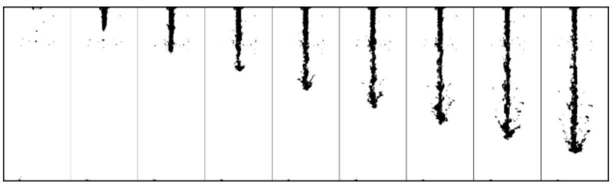
Due to the velocity difference between the jet and the surrounding water, waves could generate on the surface of the jet and then grows up, and then breakup process happen due to these waves. Figure 2 shows the jet injection behavior under different conditions: (a) without CRGTs, (b) with CRGTs at a P/D of 2.47, and (c) with CRGTs at a P/D of 1.37. Both instability and fragmentation behavior could be observed obviously at the jet side and leading edge for the case without CRGTs. Compared to the case without CRGTs, fewer jet surface disturbances and less leading edge breakup behavior could be observed for the cases with CRGTs. This is mainly due to the CRGTs limiting the jet swelling behavior, so fewer droplets could generate on the surface of the jet.



(a) Without CRGTs



(b) With CRGTs at a P/D of 2.47

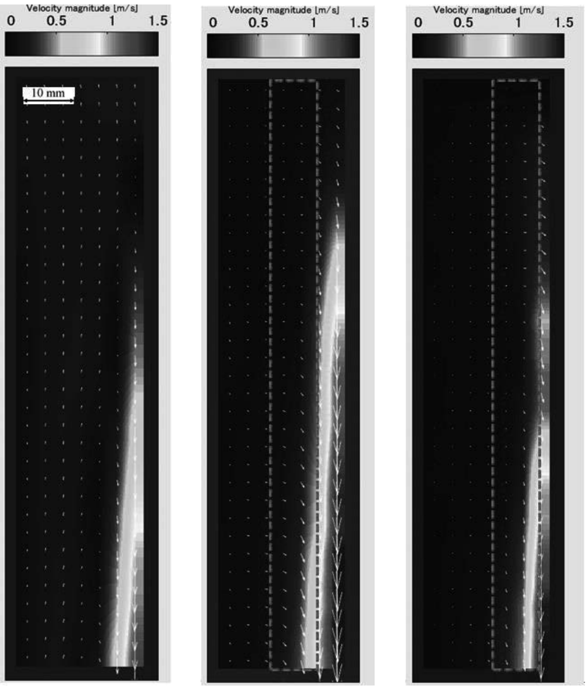


(c) With CRGTs at a P/D of 1.37

Fig. 2 Jet falling behavior with and without CRGTs

3.2 Surrounding velocity profiles of the jet via PIV method

PIV method was used to measure the water velocity profiles surrounding the jet. The water velocity profiles differences between the cases with and without CRGTs were obtained from these experiment. Figure 3 shows the average velocity profiles after the jet reached quasi-steady breakup for different conditions: (a) without CRGTs, (b) with CRGTs at a P/D of 2.47, and (c) with CRGTs at a P/D of 1.37. The CRGT positions were marked as the dashed boxes in Figure 3. The water velocity in the cases without CRGTs is smaller than that in the cases with CRGTs. In the conditions with CRGTs, the amount of water was limited in the gap between the jet and four CRGTs. In such a narrow gap, water is extensively accelerated with the jet. The water velocity increases in the axial direction for all cases.



(a) (b) (c)

Fig. 3 Water velocity profiles around the jet according to the PIV method (a) Without CRGTs (b) with CRGTs at a P/D of 2.47 (c) With CRGTs at a P/D of 1.37

3.3 Particle diameter

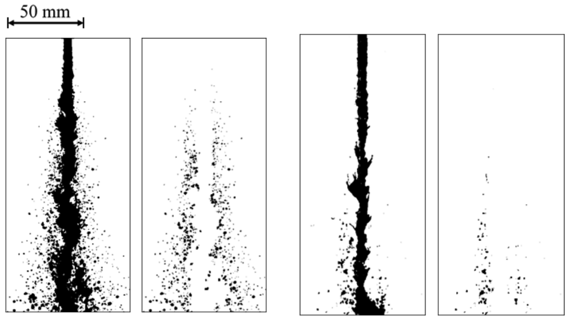
Table 1 shows the droplet Sauter mean diameter obtained from the experiments for different cases. When a droplet exists in a flow, the surface tension balances with the shear force from the relative velocity of the fluids. From the table we could see that the droplets diameter does not change significantly with or without CRGTs.

Table 1 Particles Sauter mean diameter

Jet diameter (cm)	CRGTs condition	Jet injection velocity (m/s)	Particle Sauter mean diameter (mm)
0.5	Without CRGTs	2.8	1.31
0.5	With CRGTs (P/D=1.37)	3.0	1.34
0.5	Without CRGTs	2.4	1.49
0.5	With CRGTs (P/D=1.37)	2.3	1.53

3.4 Relative breakup fraction

The CRGTs can limit the jet breakup process and few droplets could departure from jet surface when CRGTs exist. Figure 4 shows the molten droplets under different conditions: (a) without CRGTs and (b) with CRGTs (P/D = 1.37). The jet in the original image was hidden and only particles departure from the jet surface were left in the image. The ratio of the droplets surface area for the case with CRGTs to that without CRGTs, is defined as C.



(a) (b)

Fig. 4 Droplet departure from the jet surface (a) Without CRGTs (b) With CRGTs (P/D = 1.37)

Table 2 shows *C* for different conditions. Jet diameter, pitch/diameter of CRGTs and vessel pressure could affect the breakup fraction. Among all of these parameters that can affect breakup fraction, the ratio of pitch and diameter of CRGTs has stronger effect than other two parameters.

Table 2 Ratio of surface area of droplets

Jet diameter (cm)	P/D	Vessel Pressure (MPa)	*C*
0.5	1.37	0.2	0.13
0.5	1.37	0.1	0.27
0.3	1.37	0.2	0.16
0.3	1.37	0.1	0.26
0.3	2.47	0.2	0.73
0.3	2.47	0.1	0.86

Clearly, the surface area of the molten droplets could reflect the number of molten droplets, which means that the relative breakup fraction could be obtained from the surface area ratio. In current study we focus on the CRGTs effect on jet breakup fraction. The average relative breakup fraction based on P/D is shown in Table 3. The experiment results show that jet breakup fraction for the case with CRGTs (pitch/diameter ratio of 1.37) was only approximately 20% of that for the case without CRGTs, while jet breakup fraction for the case with CRGTs at a

P/D of 2.47 was only approximately 80% of that for the case without CRGTs

Table 3 Average relative breakup fractions

P/D	Average relative breakup fractions (*C*)
1.37	0.2±0.07
2.47	0.8 ±0.07

4. Conclusion

In order to investigate the effect of CRGTs on jet breakup behavior, small-scale jet breakup experiments were conducted. The following results can be obtained from the experiments.

The surrounding water velocity profile in the case without CRGTs is smaller than the cases with CRGTs by the PIV method. The droplets diameters does not change significantly with or without CRGTs. CRGTs can restrain the jet breakup process. The relative breakup fraction was used to evaluate the jet breakup fraction when CRGTs exists. For the case of CRGTs at a P/D of 1.37, the relative breakup fraction was recommended as 0.2, while for the case of CRGTs at a P/D of 2.47, the relative breakup fraction was recommended as 0.8.

Reference:

[1] Sehgal, B.R., "Nuclear safety in light water reactors: Severe accident phenomenology", Academic Press, New York (2011).

[2] Saito R, Abe Y, Yoshida H (2014) Experimental study on breakup and fragmentation behavior of molten material jet in complicated structure of BWR lower plenum. J Nucl Sci Technol 51(1):64–76.

[3] Abe Y, Matsuo E, Arai T, Nariai H, Chitose K, Koyama K, Itoh K (2006) Fragmentation behavior during molten material and coolant interactions. Nucl Eng Des 236(14–16):1668–1681.

[4] Bang KH, Kim JM, Kim DH (2003) Experimental study of melt jet breakup in water. J Nucl Sci Technol 40(10):807–813.