An Experimental Study on Flow Boiling CHF Characteristics of Partially Narrowed Tube

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1. Introduction

To prevent release of radioactive material into environment, multiple barriers are main concept of nuclear safety which consist of nuclear fuel pellet, fuel cladding, reactor vessel, and containment building. All parts should maintain their integrities even in severe accident condition. Among them, fuel cladding is mainly focused in this paper.

In normal operation condition of nuclear power plant, cladding keeps its integrity. In severe accident condition, especially for propagation consequence of LOCA(Loss of coolant accident), coolant in reactor vessel can be disappeared and then nuclear fuel rod will be exposed into atmosphere without coolant. Then the residual heat of nuclear fuel cannot be removed, the surface temperature of cladding will be increased. There is a possibility of cladding rupture without any management. In those circumstances, some studies showed that fuel cladding will be deformed in ballooning shape before cladding rupture. The ballooning of fuel cladding means narrowing of subchannel simultaneously. The flow path is partially narrowed through the subchannel, so it can affects on flow and thermal characteristics obviously. Furthermore, the significantly narrowed subchannel can totally block the coolant by re-flooding from safety injection.

Critical heat flux, CHF is an important thermal hydraulic phenomenon because it can cause a rupture of the heating surface with dramatic temperature increase. The CHF of fuel cladding is also very important because it is directly related to release of radioactive material.

There are not many studies on thermal hydraulic characteristics of partially narrowed channel like deformed nuclear fuel rod in accident condition. In this study, CHF characteristics of partially narrowed channel modeled from deformed nuclear fuel cladding were experimentally investigated.

2. Experimental Apparatus

2.1 Experimental Loop and Procedure

The experiment was conducted on KAIST flow boiling CHF experimental loop. The KAIST flow boiling test loop is shown in Fig. 1. The test loop is composed of a pump, an electromagnetic flow meter, an electric pre-heater, test section, a condenser, and a surge tank. Water is working fluid of the test loop.

The water was circulated in the test loop by a pump and it flows vertically upward through the test section tube. The signals of mass flux, inlet temperature, pressure and surface temperature of test section were acquired by data acquisition system, Agilent 34972A, and then it transmitted to the PC.

For heating up the test section, direct Joule heating method was used. Electric power was provided by the DC rectifier which has specification of 25V*3000A, 75kW.

The experimental procedure is as follows. First, test condition should be set up. The mass flux of working fluid and inlet temperature is calibrated before heating up the test section. After setting up the initial condition, heating experiment is started. The electric power is hanged on to the top and bottom part of the test section through copper electrode. The test section is heated up gradually by slowly increasing the hanging voltage of the test section. The heating power is increased step wisely after thermal equilibrium of the working fluid in the loop. The surface temperature of test section was measure by K type thermocouples. The tip of each thermo couple was contacted on the test section surface by ceramic jig around the test section.

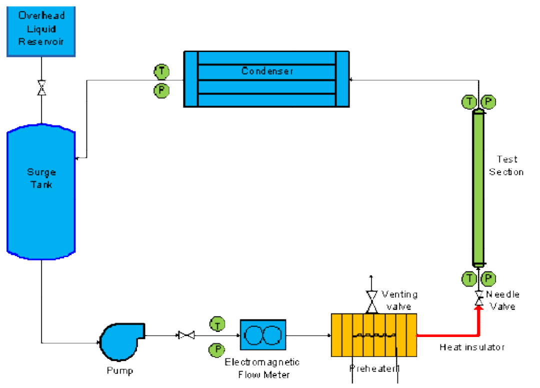

Fig 1. Schematic diagram of KAIST flow test loop

CHF point was detected by sudden increase of the surface temperature, observation of surface burnout into bright red-yellow color with naked eyes, or decrease of hanging electric power on test section without any human control on electric power.

All tests were conducted under atmospheric pressure.

2.2 Design of Deformed Test Section and Heat Flux Calculation

The test section was modeled from the shape of deformed(especially ballooning) nuclear fuel rod in case of accident. The Schematic diagram of deformed test section is shown in Fig. 2.

The section is composed of 5 parts. L1 and L5 are inlet and outlet parts respectively and they represents the original flow path without any deformation. L3 depicts the narrowed channel between nuclear fuel rods due to ballooning. L2 and L4 are the simplified linkage flow path between original and deformed channels. Each part of test section(L1~L5) is bonded together by outside welding. The length of each part was set as 100mm, 50mm, 200mm, 50mm, and 100mm from L1 to L5 respectively.

T1~T5 mean the place of thermo couple which surface temperature was measured.

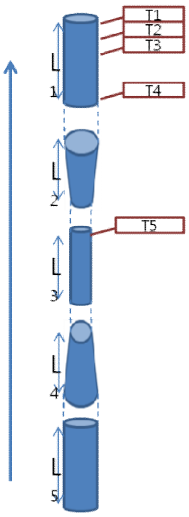

Fig 2. Deformed Test Section

The 2 different original inlet inner diameter(for L1, and L5) was conducted, 10mm and 8mm. For 10mm original inlet diameter, three kinds of narrowed channel(L3) with different inner diameters were conducted, 8mm, 6mm, and 4mm. For 8mm original inlet diameter, two kinds of narrowed channel(L3) with different inner diameters were conducted, 6mm, and 4mm. Each test was conducted for 2 kinds of inlet subcooling condition, 50K and 25K. The test matrix conducted in this study is as shown below, Table 1.

Table 1. Test Matrix

Inlet I.D. [mm]	Deformed I.D.[mm]	Blockage ratio[%]	Inlet mass flux[kg/m^{2}s]	Inlet subcooling[K]
10	8	36	100, 200	50,25
	6	64		
	4	84		
8	6	44		
	4	75		

The thickness of the tube is 1mm for whole part of the tube so the mass flux and heat flux is different from part to part. The difference of mass flux is shown in Table 2.

Table 2. Mass flux transition in narrowed channel

a) For inlet inner diameter 10mm

For Inlet I.D 10mm	Narrowed channel inner diameter[mm]		
	8	6	4
100kg/m^{2}s	156	278	625
200kg/m^{2}s	312	556	1250

b) For inlet inner diameter 8mm

For Inlet I.D 8mm	Narrowed channel inner diameter[mm]	
	8	6
100kg/m^{2}s	178	400
200kg/m^{2}s	356	800

Heat flux in the test section is basically calculated as

$$q' = \frac{VI}{\pi D\,L}$$

where V and I are the measured voltage and current, D is the diameter of test tube and L is length of test section.

Through the test section, heat flux on each part will be different by their different surface area. The power is hanged on the whole test section and the same current will be hanged on each part. The heat fluxes for each part were calculated from the measured total electric power, current at that time and partial area ratio.

3. Results and Discussion

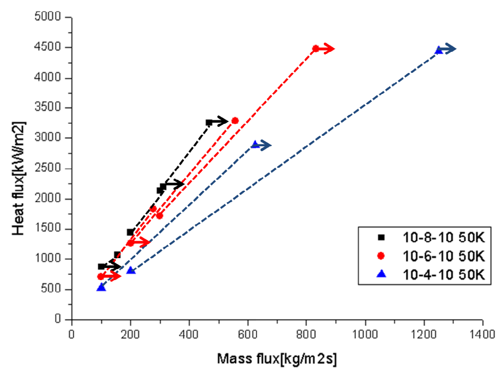

Fig 3. CHF data for Inlet I.D 10mm experiment

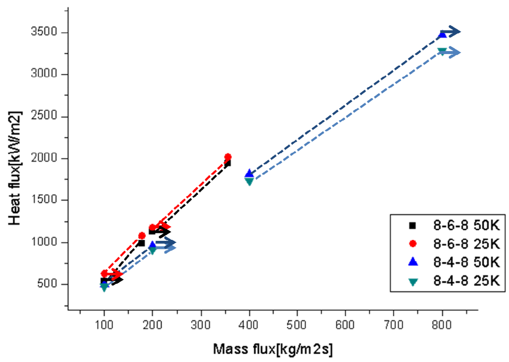

Fig 4. CHF data for Inlet I.D 8mm experiment

The experimental results are shown in Fig 3. and Fig 4. The dot line(⋯) means that linked two points show two different mass and heat flux in one test section. The arrowed line(→) means the point that CHF occurred.

For inlet I.D 10mm, low blockage ratio(36,64%) and low mass flux(100kg/m^2s), CHF occurs at the end of the test section, not at the narrowed channel. Other cases, all points of higher blockage ratio for inlet I.D 10mm and 200kg/m^2s mass flux cases for lower blockage ratio, CHF occurred end of the narrowed channel.

For inlet I.D 8mm, only 44% blockage ratio and 100kg/m^2s test case, CHF was occurred at the end of the test section. Except that point, all CHF points were at the end of the narrowed channel.

The experimental results describe that CHF is occurring at the narrowed channel with high blockage ratio(>70%) and high mass flux(>200kg/m^2s). With lower blockage ratio(<70%) and low mass flux(<100kg/m^2s), CHF occurs at the end of whole test section.

Qualitatively, the transition of CHF point is mainly considered as phase change of flow regime with mass flux change. If condition of boiling crisis is at the liquid film dryout condition(lower mass flux), CHF will occur at the end of the whole test section. If blockage ratio gets higher than 70%, CHF will occur at the narrowed channel even mass flux is low. Vice versa, if the mass flux is high, which means that condition of boiling crisis is at the departure of nucleate boiling condition, CHF will occur at the narrowed channel. The generating bubble in the flow channel will be easily gathered in the narrowed channel due to its physical circumstance, CHF will easily occur at that point.

4. Conclusion

The result of CHF experiment for partially narrowed channel was reported. The trends of CHF point was found dependent on blockage ratio and mass flux. With lower mass flux and lower blockage ratio, the point of CHF was at the end of the whole test section. With higher mass flux and higher blockage ratio, point of CHF was moved to the narrowed channel. The reason of transition of test section was discussed as interaction between physical environmental change of test section and effect of flow regime transition. For more detailed and qualitative analysis, more experimental cases are under operation.

Acknowledgement

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