An Experimental Study on Flow Boiling Critical Heat Flux Characteristics of Suddenly Expanded Region

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1. Introduction

Cladding, which is a part of defense in depth system to prevent radiation leakage toward environment, can be deformed in severe accident condition. Deformed cladding changes coolant flow path so cooling of core can be disturbed. Core should be cooled even after accident to mitigate further accident progress. Thus, data of heat transfer characteristics in deformed cladding should be gathered to enhance safety of nuclear power plant in accident condition. In this experiment, test section has been designed to simulate sudden flow path change due to deformation of cladding. It was tended to simulate cladding deformation that has discontinuous diameter change so coolant flow path changes suddenly. Experiments are in progress.

2. Experimental Apparatus

2.1 Experimental Loop and Procedure

CHF measurement experiments were conducted on KAIST flow boiling experimental loop which is shown in Fig. 1. Flow boiling loop is composed of a pump, an electromagnetic flow meter, an electric pre-heater, a condenser and a surge tank. Water was used as working fluid. Maximum power of rectifier used to heat test section was 75kW DC, which has specification of 25VX3000A. Data for mass flow, temperature and pressure are gathered by data acquisition system Agilent 34972A.

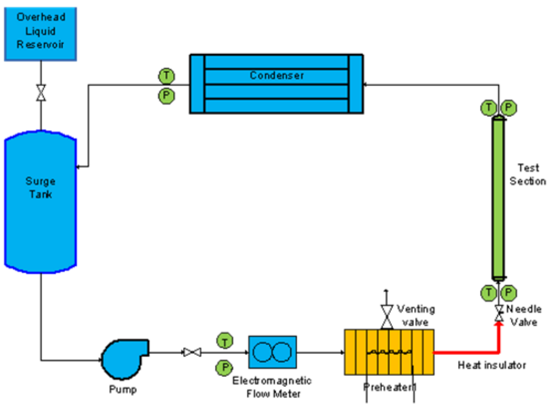


Fig. 1. Schematic diagram of KAIST flow test loop

Before experiment, mass flux and inlet temperature were controlled by pump and pre-heater. Electric power of rectifier was increased after thermal equilibrium of the working fluid in the loop was achieved. It leaded to heat flux increment, which was about 20kW/m^2 per each step. It continued until CHF occurs in test section, which was detected by sudden temperature rise or sudden glowing of test section.

Test matrix for experiments is shown in Table I. Experimental loop was under atmospheric pressure and water flowed vertically upward. Four mass flux condition and two inlet subcooling condition expanded data range of experiment.

Table I. Test matrix

Uniformly Heated Vertical Upward Flow	
Pressure(kPa)	101.3
Inlet Mass Flux(kg/m^{2}s)	50, 100, 150, 200
Inlet Subcooling(˚C)	50, 25
Working Fluid	Water

2.2 Design of Test Section

In this experiment, gradual diameter changing part of test section used in previous experiment has removed and tubes that have different diameter connected directly. SUS304 tubes were connected by low temperature welding method to prevent change of properties of tube in welded part.

Thickness of test section was adjusted to give uniform heat flux along the test section. Required test section thickness for uniform heat flux was calculated by using electrical current and resistance. Test section can be seen as electrical resistance connected in series so electrical resistance I is uniform along the test section. On the other hand, electrical resistance varies by diameter and thickness of tube. Following equation shows relation of heat flux and thickness. ρ is specific resistance, t is wall thickness and D is diameter of tube.

$$q'' = \frac{I^2R}{\pi DL} = \frac{\rho I^2}{\pi^2}\cdot\frac{1}{Dt^2 + D^2t} \qquad (1)$$

Geometry of test section and location of thermocouples are shown in Fig. 2. Five thermocouples are located from sudden contraction point of test section to test section outlet.

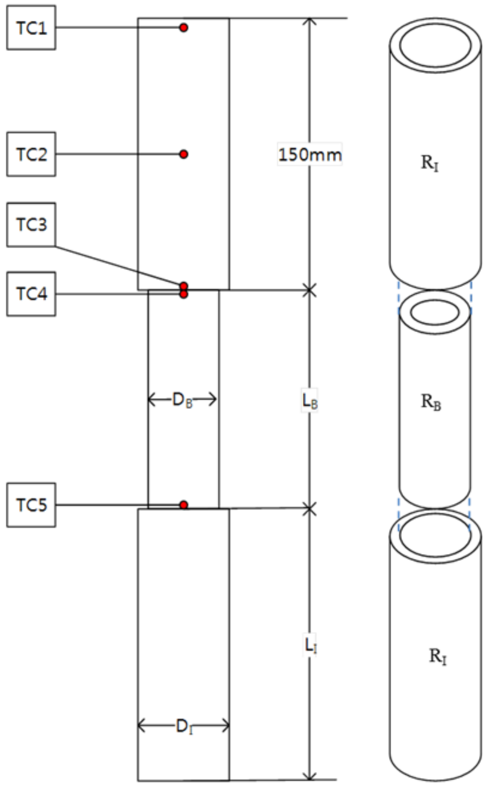


Fig. 2. Test section and location of thermocouples

Specific geometry information of test section is shown in Table II. Until now, experiments on three blockage ratio and two blockage length were carried on and two blockage ratio conditions, which have inlet diameter as 8mm and blocked diameter as 6 and 4mm each, will be further progressed.

Table II. Geometry of test section

Inlet Diameter D_I	**Blocked Diameter D_B**	**Blockage Ratio ε**	**Wall Thickness for Blocked Part**
10mm	8mm	36%	1.45mm
	6mm	64%	2.23mm
	4mm	84%	3.61mm
Total Heated Length	**Length before Blockage L_I**	**Blocked Length L_B**	**Length after Blockage**
500mm	200mm	50mm	150mm
	150mm	100mm	150mm

3. Results and Discussion

In this experiment, location of CHF has been changed by experimental cases. It is sorted in Table III. by mass flux and blockage ratio. CHF occurred at test section outlet for the cases of blank cells and CHF occurred at sudden expansion part for the cases of shaded cells. Slashed cells are regarded as boundary between two locations of CHF because value of CHF has changed even in same condition.

Table III. Experimental cases sorted by the location of CHF

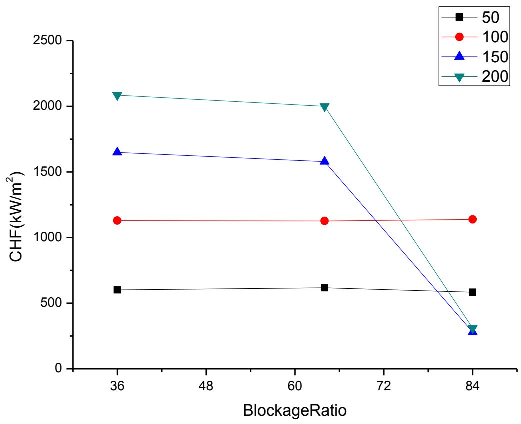
Mass Flux(kg/m²s) / Blockage Ratio(%)	**50**	**100**	**150**	**200**
36				
64				///
84				

(a) Blockage Length : 50mm

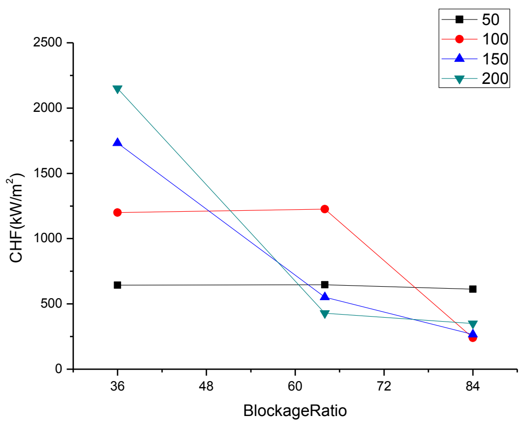
Mass Flux(kg/m²s) / Blockage Ratio(%)	**50**	**100**	**150**	**200**
36				
64			///	
84		///		

(b) Blockage Length : 100mm

Experimental results for 50K subcooling condition are shown in Fig. 3. Results were arranged by blockage ratio. For results of "Boundary" conditions, lowest heat flux value among many cases was used.



(a) Blockage length: 50mm



(b) Blockage length: 100mm
Fig. 3. Experimental results for 50K subcooling

3.1 CHF at Test Section Outlet

In low blockage ratio experiment and high blockage ratio with low mass flux experiment, CHF occurred at the outlet of test section. Compared to the Macbeth's CHF correlation for low pressure and low mass flux, data showed good agreement. The Macbeth's CHF correlation for local condition is

$$q'' = 0.1502 h_{fg} D^{-0.1} G^{0.51} (1 - X) \qquad (2)$$

Differences between prediction by correlation and experiment were less than 10% in these cases. Values were also similar to data of reference experiments of flow boiling experiments on plain tube. Representative result for 36% blockage ratio and 50K subcooling is shown in Fig. 4.

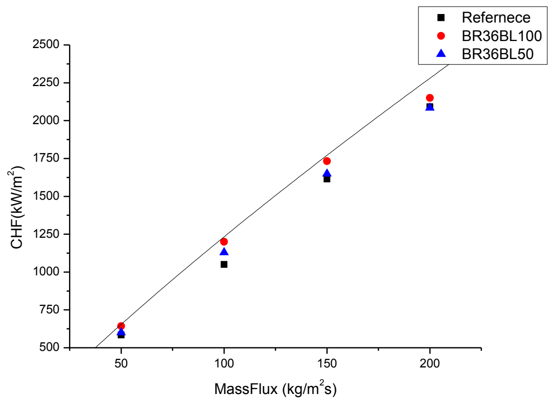


Fig. 4. Comparison with reference experiments and correlation

As shown in Fig. 4., results showed little difference between experiments on two different blockage length. Difference of CHF comes from increased mass flux and reduced diameter in deformed part. Mass flux increment is proportional to square of diameter so its effect is higher than reduced diameter in this part. Value of mass flux G times diameter D, which affects quality increment and pressure along the flow path, becomes larger as blockage length becomes longer or blockage ratio becomes higher. Due to larger GXD, quality increased less and pressure dropped more in blockage part so CHF was slightly enhanced. However, it enhanced slightly and it was in range of measurement error.

3.2 CHF at Sudden Expansion Part

In high blockage ratio with high mass flux experiment, CHF occurred at sudden expansion point of test section. CHF happened in low heat flux region, around 200~400kW/m^2 and it is shown in Fig. 3.

Flow regime of these cases was churn flow regime. During experiment, it was first recognized from visualization part located after test section outlet. Then, it was calculated and confirmed by using the Hewitt and Robert flow pattern map(1969). It is shown in Fig. 5. Black dots are the calculated results for experimental cases.

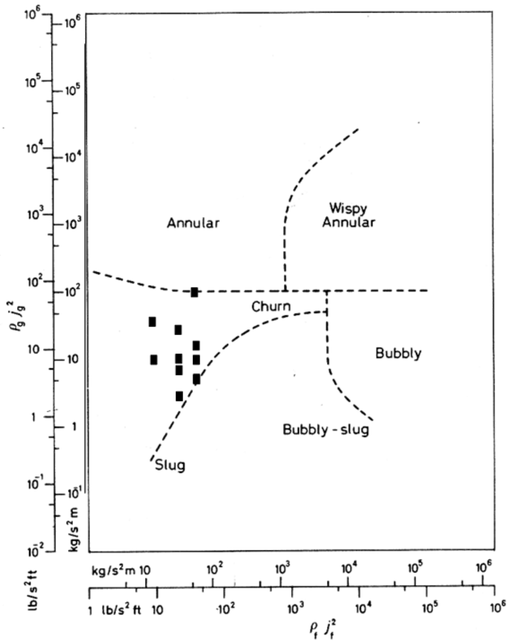


Fig 5. Flow regime for CHF occurred at sudden expansion part

Until now, it seems that this result comes from liquid film separation from wall or bubble accumulation by backflow at sudden expansion part. Also, OSV calculation for these experimental conditions will be done for further research. Because of very low CHF value and churn flow regime, it seems there is some relation with OSV and early CHF of this experiment.

3.3 Boundary Condition

As explained earlier, results for slashed cells in Table III. changed when experiments on same condition was iterated. In some cases, it reached almost same value of predicted CHF, about 1500kW/m^2 for 150kg/m^{2}s mass flux. On the other hand, early CHF occurred in most cases. However, value of early CHF was much higher than CHF at sudden expansion part. Therefore, it is discussed as boundary condition for location of CHF in deformed channel. Further experiments and discussion will be held on.

4. Conclusion

Experiments on test section that simulate deformed flow path which contains sudden contraction and sudden expansion part have been done. Location of CHF has been varied by different condition of experiment. CHF at the outlet of test section fits well into the Macbeth's correlation and data of reference experiment, which was held on plain test section that had same diameter with inlet diameter of deformed test section. CHF at sudden expansion part was in churn flow regime and CHF was very low compared to expectation. It is discussed that liquid film separation from wall or bubble accumulation by backflow might be the reason of this result. For future work, experiments for two additional blockage ratio conditions will be carried out. Also, discussion and model development for deformed channel with sudden expand flow path will be held on.

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