Experimental investigation on the CHF in the narrow rectangular channel under the downward flow condition

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1. Introduction

The new research reactor under constructing in Ki-jang adopts a plate-type-fuel with downward flow cooling to prevent release of radioactive substance at pool surface. The thermal hydraulic design for the narrow rectangular channel differs from that for rod bundle channel. The licensing for construction of research reactor requires thermal hydraulic safety analysis of narrow rectangular channel. In the thermal hydraulic safety analysis, critical heat flux (CHF) on the fuel surface is considerably important to determine power and safety margin. The objectives of present study are, therefore, to carry out the experiment of CHF for downward flow in narrow rectangular channel, to obtain the correlation of CHF prediction applicable to a subchannel of plate-type-fuel.

2. Experiment

2.1 Test facility

Fig. 1 presents a schematic diagram of test facility which consists of a flow loop, a cooling system and a test section with a narrow rectangular channel. The flow loop is closed loop consisting of a pressurizer, a water tank, a pump, a coriolis mass flow meter, a preheater, a bypass line, a separator, a condenser, a heat exchanger, a control valve and glove valves. The flow directions in a test section can be changed by adjustment of valves as shown in Fig. 1. The preheater keeps the inlet coolant temperature at a target value. The cooling system consisting of a condenser and heat exchanger remove heat generated by fuel simulator installed in the test section. The test section has an upper and lower plenum and simulate a subchannel of plate-type-fuel as shown in Fig. 2. The configuration of flow channel is presented in Table I. Type1 is designed for fission moly target in research reactor. The other type simulates a full scale subchannel of plate-type-fuel element. The heaters are made of Invar 36 with 0.8 mm in thickness. To detect CHF, sheathed thermocouples of which O.D. is 1/16″ are installed on the back surface of heater and a CCD camera is also installed near the exit of test section for the detection of red colored light generated from heater plate when CHF occurs. The inlet and outlet coolant temperatures and pressures are measured with thermocouples and pressure transmitters, respectively, at the both ends of flow channel.

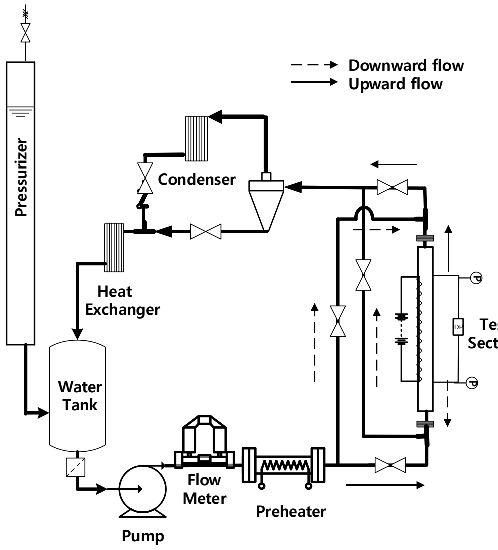

Fig. 1. Schematic of a main loop

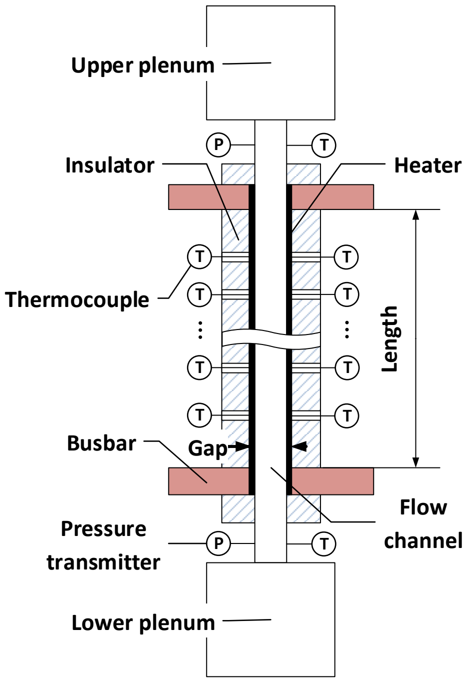

Fig. 1. Schematic of a test section

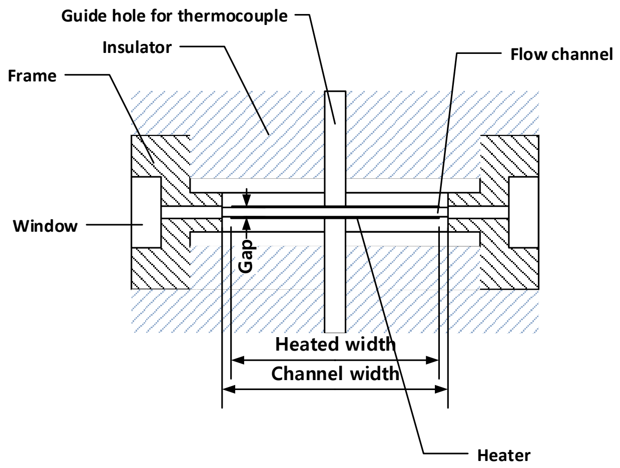

Fig. 2. Detailed cross-sectional view of test section

Table I: Test section geometry

Test section	Type1	Type2
Channel width (mm)	44.6	66.6
Heated width (mm)	40.0	62.0
Gap (mm)	2.58	2.35
Length (mm)	182	640

2.2 Experimental conditions

The major parameter affecting on the CHF are flow direction, mass flux, temperatures and pressures. The test conditions are determined with these parameters listed in Table II. The test procedures are as follows. The deionized water is prepared as coolant. The non-condensable gases in the water were removed by degassing operation before CHF test. The inlet temperature is maintained at a target value by the preheater control. The heater power is increased step wisely until the CHF occurs. The CHF is detected by temperatures of heater or the red colored light emitted from the heater surface due to the high temperature. Once CHF occurs, the electric power supply is immediately shutdowned by the trip circuit.

Table II: Test condition

Flow direction	Downward flow
Heater power (kW)	9-189
Heat flux (kW/m^2)	538-4026
Mass flux (kg/m^2-s)	276-2739
Inlet fluid temperature(℃)	37-80
Outlet pressure(kPa)	120-224

3. Test results and discussion

3.1 Previous studies
3.1.1 Mishima correlation [1]

Mishima developed a CHF correlation applicable to the low flow rate and low pressure conditions as the Eq. (1), by using the CHF data. Mishima reported that the minimum CHF occurs at a mass flux less than the flooding mass flux. Additionally, CHF at higher mass flux occurs when water temperature at the outlet reaches to saturation.

$$q^*_{CHF} = 0.7\frac{A}{A_H}\frac{\sqrt{W/\lambda}}{\left\{1+\left(\rho_g/\rho_l\right)^{1/4}\right\}^2} \quad (1)$$

3.1.2 Kaminaga et al. correlation [2, 3, 4]

Kaminaga et al. developed a CHF correlation which is formulated as Eqs. (2)&(3) to simulate a subchannel in the fuel element of research reactor JRR-3. It is based on the Mishima correlation. They found that CHF scheme depends on the mass flux.

$$q^*_{CHF,1} = 0.005\left|G^*\right|^{0.611}\left(1+\frac{5000}{\left|G^*\right|}\Delta T^*_{SUB,o}\right) \text{ for } G^* \geq G^*_1 \quad (2)$$

$$G^*_1 = \left(\frac{0.005}{\frac{A}{A_H}\Delta T^*_{SUB,in}}\right)^{\frac{1}{0.389}} \quad (3)$$

3.2 Development of a new CHF correlation

A new CHF correlation is developed in present study by considering Mishima and Kaminaga et al. correlations. Mishima proposed a minimum CHF and CHF correlation for the downward flow. Kaminaga et al. found that CHF is proportional to dimensionless mass flux to the power 0.611. In present study, authors developed CHF correlation by adopting dimensionless mass flux calculated with measured CHF data. Eq. (4) is a newly developed CHF correlation to predict CHF for the narrow rectangular channel with both sides heating under the downward flow condition. Fig. 4 shows the comparison of CHF data predicted by correlations.

$$q^*_{CHF} = \frac{A}{A_H}\left[6.78\Delta T^*_{SUB,in}G^{*0.611} + \frac{0.7\sqrt{W/\lambda}}{\left\{1+\left(\rho_g/\rho_l\right)^{1/4}\right\}^2}\right] \quad (4)$$

The prediction errors are calculated for each data point. Details of the evaluated error are presented in Table III. The table show new correlation under predict the CHF. But the RMS error of the newly developed correlation are less than that of the Kaminaga et al. correlation.

Table II: Error statistics of correlation

Correlation	Kaminaga et al.	New correlation
Avg. error	0.6%	-3.0%
RMS error	22.6%	20.2%

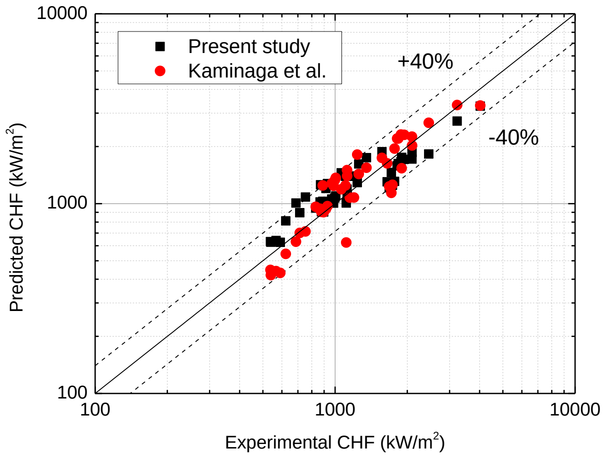

Fig. 4. Comparison of CHF prediction for downward flow against the data

4. Conclusions

CHF experiments were carried out in the narrow rectangular channel simulating plate-type-fuel for research reactors under the downward flow condition. With the investigation of CHF data of the present experiment and previous studies, a new CHF correlation was proposed for the downward flow in the subchannel of plate-type-fuel. The predicted CHF by the new CHF correlation shows good agreement with experimental data in the present study. However, the correlation was based on the limited number of experimental data under low-flow conditions. Therefore, further studies for more data are needed to generalize the CHF correlation.

NOMENCLATURE

A : Flow area (m^2)

A_H : Heated area (m^2)

G : Mass flux (kg/m^2s)

G^* : Dimensionless mass flux

$\left(=G\big/\sqrt{\lambda\left(\rho_l-\rho_g\right)\rho_g g}\right)$

g : Acceleration of gravity (m/s^2)

h_{fg} : Latent heat (kJ/kg)

L : Channel length (m)

q_{CHF} : Critical heat flux (kW/m^2)

q^*_{CHF} : Dimensionless CHF

$\left(=q_{CHF}\big/h_{fg}\sqrt{\lambda\left(\rho_l-\rho_g\right)\rho_g g}\right)$

$\Delta T_{SUB,in}$: Subcooling (K)

$\Delta T^*_{SUB,in}$: Dimensionless subcooling

$\left(=C_p\Delta T_{SUB}/h_{fg}\right)$

W : Channel width of rectangular channel (m)

ρ_g, ρ_l : Density of gas and liquid (kg/m^3)

σ : Surface tension (N/m)

λ : Critical wave length (m)

$\left(=\left\{\sigma/\left(\rho_l-\rho_g\right)g\right\}^{1/2}\right)$

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