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CHF experiments of SUS304 heater at 30 and 60 degree inclination angles with downward facing geometry for IVR-ERVC

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1. Introduction

To mitigate severe accident, APR1400 adopt IVR-ERVC (In-Vessel Retention through External Reactor Vessel Cooling) strategy. The goal of the IVR-ERVC is to keep molten corium inside the reactor vessel and terminate the accident propagation. To achieve that, it is necessary to remove decay heat from the molten corium. During the IVR-ERVC, the reactor vessel will be flooded, and the decay heat will transfer from the corium to cooling water. Therefore, it is one of major issues to know the heat transfer limit on that heat transfer process, and CHF (Critical Heat Flux) can represent it. This is because the heat transfer mode changes from the nucleate boiling region to the film boiling region which has very low heat transfer coefficient, when the heat flux exceed the CHF value. From this reason, it is important to know the CHF values and many related studies are under way.

2. Experimental Apparatus, Method and Condition

Experimental apparatus, method and condition are presented in this section. In experimental apparatus, the design and dimension of apparatus are described. The experimental method explains process of experiment and how the CHF value be measured. Finally, in the experimental condition, thermal hydraulic conditions of the conducted experiments are summarized.

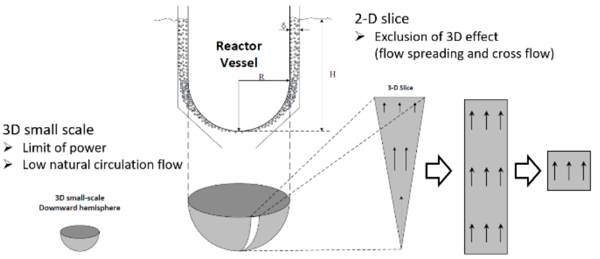


Fig. 1. Schematic diagram of the scale down process of vessel for experiment

2.1 Experimental Apparatus

The main purpose of this research is measuring the CHF data under the IVR-ERVC thermal hydraulic conditions, and thus it is necessary the experimental apparatus properly simulates the conditions of IVR-ERVC. The real reactor vessel has the 2.5 m of radius curvature, and estimated decay heat power is order of MW. This dimension and power are too large scale for lab. scale experiment. Therefore, in this experiment, 0.5 m of radius curvature are considered. There is no scaling effect on the CHF between 2.5 m and 0.5 m of radius curvature [1]. Fig.1 show the scale down concept.

Flow path is formed by thermal insulation wall that minimizes heat loss of the vessel at normal operation, and, under the IVR-ERVC, the coolant is naturally circulated through the flow channel because of density difference between inside and outside of the thermal insulator. This natural circulation was evaluated about ~ 500 kg/m^{2}s in mass flux [2]. To simulate this circulation flow condition and control the mass flux of it, overall experimental apparatus was designed as loop and forced circulation type.

Schematic diagram of the experimental loop is shown at Fig. 2. The pump and flow meter controls and measures the fluid mass flux, the water temperature controller heats up the working fluid up to experiment temperature, heat exchanger and surge tank condenses and eliminates the generated vapor, and air supply & venting line control the system pressure. The working fluid is DI water. Two k-type thermocouples measure the working fluid temperature at lower plenum and water temperature controller. The pressure transmitter measures the system pressure at the top of surge tank. The test section simulates the location of the CHF occurrence, which means the maximum heat flux location of the reactor vessel. The region of preheater simulates the heat flux distribution of the reactor vessel lower head to make proper thermal hydraulic condition. All components are connected by SUS304 pipe. The test section and preheater region have rectangular water channel geometry.

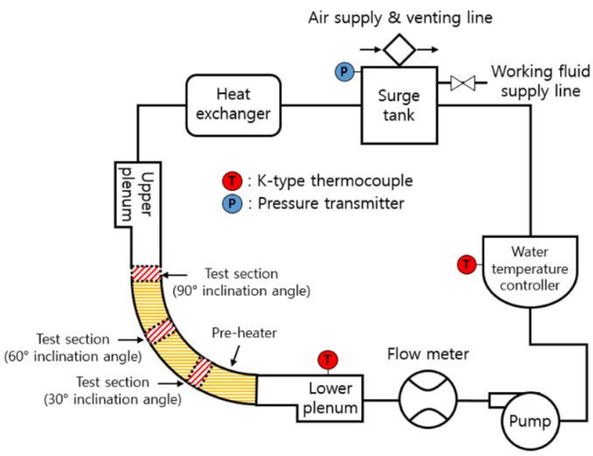


Fig. 2. The experimental flow loop schematic diagram

Fig. 3 shows the picture of test section and specimen. The specimen is also called main heater, and is heated up by direct joule heat method until the surface heat flux reaches the CHF value. The test section is composed with the main heater and structures to make downward facing heat transfer flow channel. The detail geometry of the main heater and flow channel are summarized at experimental condition section.

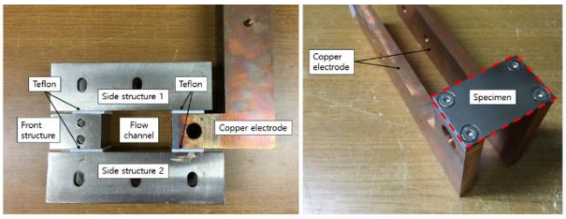


Fig. 3. Picture of test section (left) and specimen (right)

2.2 Experimental Method

In this section, the experiment process and the CHF measurement method are described.

Firstly, it is about the experiment process. When the working fluid reaches to the experiment temperature, gradually increase the preheater's heat flux to designed heat flux distribution. After that, increase the main heater's heat flux step by step: increase 50 kW/m^2 of heat flux per 1 ~ 2 minutes, and maintain the heat flux for 1 ~ 2 minutes to make it steady state. Then repeat the process unit the CHF occurs at the main heater.

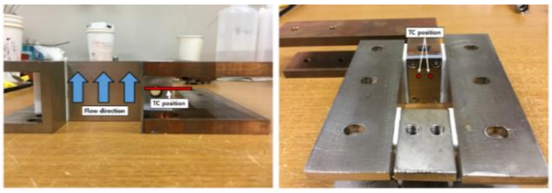


Fig. 4. Picture of test section with TCs location (left: side view, right: top view)

Secondly, it is the way how detect the CHF occurrence. When the CHF occurs, the heater wall temperature is dramatically, because of low heat transfer coefficient of film boiling region. Therefore, in this experiment, thermocouples are used to detect the sudden temperature increasing. Fig. 4 shows the location of the thermocouples. The two of k-type thermocouple measure the back side of the main heater. Fig. 5 shows the temperature profile with 0.5 s time step, near the CHF occurrence timing, and it is shown that the temperature suddenly increases, when the CHF occurs.

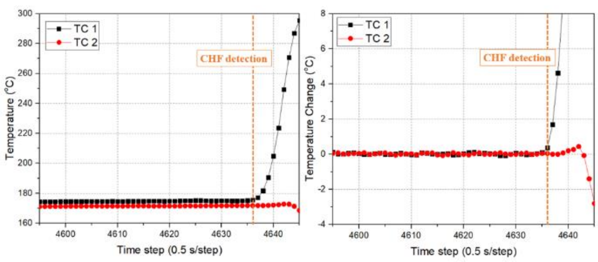


Fig. 5. Temperature profile of the main heater back side (left: temperature, right: temperature change)

During the experiments, the all voltage and current value applied to the main heater were recorded with time data. Therefore, the CHF value can be calculated by Eq. 1.

$$q''_{CHF} = \frac{Power}{Heat\ transfer\ area} = \frac{Voltage \times Current}{Heat\ transfer\ area} \quad \text{Eq. 1}$$

2.3 Experimental Conditions

In this study, the experiments were conducted with down ward facing heat transfer geometry. Inclination angle, pressure and inlet quality effect were considered. In this section, the experimental conditions were summarized at Table 1. The inlet quality was controlled by adjusting the power of preheater which explained at Fig. 2.

Table 1. Experimental conditions

Overall information		
Radius curvature (m)	0.5	
Channel gap (m)	0.06	
Channel width (m)	0.03	
Working fluid	DI water	
Inclination angle	30 °	60 °
Pressure (bar)	1, 2, 4	1, 2
Inlet quality	– 0.003 ~ 0.005	
Mass flux (kg/m^{2}s)	100, 300	
Inlet subcooling (K)	2	
Heater material	SUS304	
Main heater geometry		
Active width (m)	0.03	
Active length (m)	0.03	
Thickness (mm)	1.2	

3. Results

In this section, the inclination angle, pressure and inlet quality effect on the CHF are presented and discussed.

3.1 Inclination angle effect

Experiments were conducted for 30 and 60 ° inclination angle of downward facing heat transfer geometry. At the same time, the pressure was controlled from 1 to 4 bar. Fig. 6 shows the CHF result for inclination angle effect. Under the both pressure conditions, the CHF shows the higher value with increasing of the inclination angle. Depends on the inclination angle, buoyancy force is divided into two forces. One has parallel direction to the heat transfer surface, and hence this force (F_p) helps to remove the vapor from the surface, and consequently it induces the high CHF value. However, the other force (F_v) has vertical direction to the surface, and it makes the vapor stay near the surface. It means that this force has assistance to make the low CHF value. These things are illustrated on Fig. 7, and finally, the CHF value is degraded and enhanced at low and high inclination angle conditions respectively. From this mechanism, the CHF value is affect by the inclination angle and Fig. 6 shows it.

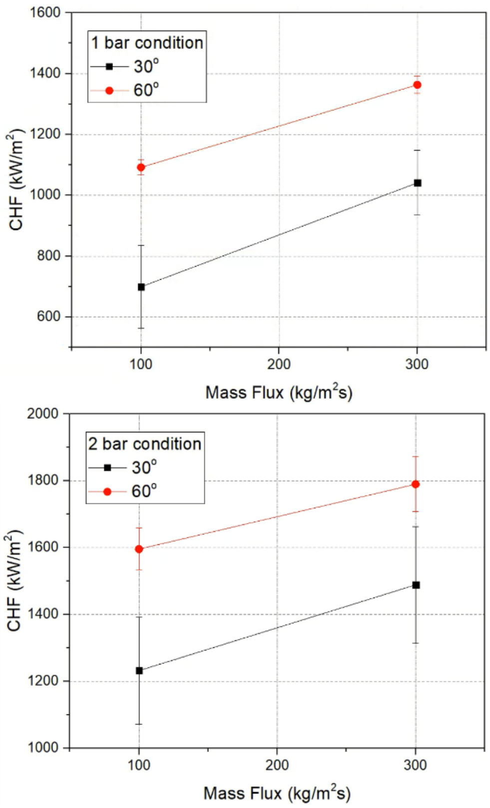


Fig. 6. Effect of inclination angle on the CHF (top: 1 bar condition, bottom: 2 bar condition)

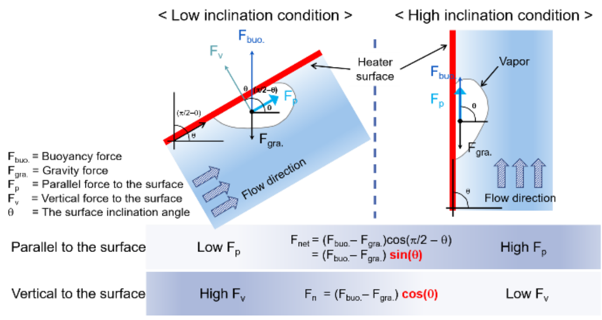


Fig. 7. Schematic diagram of force balance at flow boiling condition.

3.2 Pressure effect

Experiments were conducted under 1, 2 and 4 bar, with 30 and 60 ° inclination angle of downward facing heat transfer geometry. In general, the vapor is constricted by pressurizing, and it means that extra vapor is necessary to cover the heater and hence, at the same time, the higher CHF value is induced. Fig. 8 shows the CHF result under 1, 2 and 4 bar condition with two inclination angle conditions. For both inclination angle conditions, the higher pressure condition makes the higher CHF value. However, from the 30 ° condition result, the relation between the pressure and the CHF is not proportional over than 2 bar. It means that the pressure effect is less dominant for the CHF value after it is pressurized. However, the CHF increases with the pressurizing, this result shows the same trend with the previous research [3].

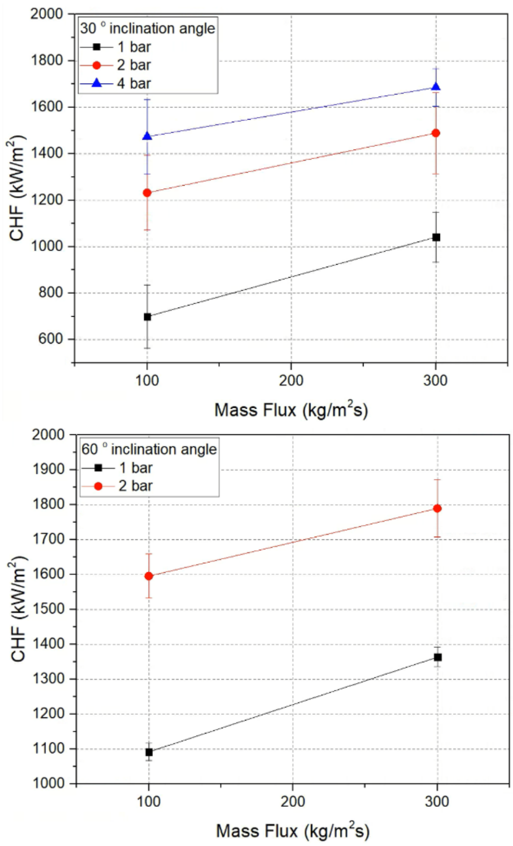


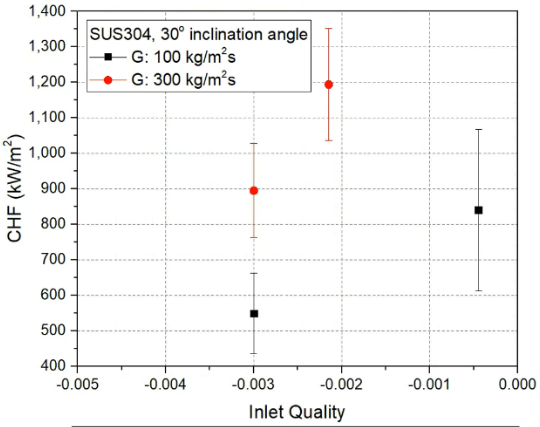
Fig. 8. Effect of pressure on the CHF (top: 30 ° angle condition, bottom: 60 ° angle condition)

3.3 Inlet quality effect

In this experiment, to control the inlet quality for the main heater, the power of preheater was adjusted under 1 bar condition. The CHF value is commonly degraded with inlet quality increasing [3], because the high quality is already high enthalpy condition and it means the low heat flux can make relatively abundant vapor. However, in this experiments, it was shown that the enhanced CHF value with inlet quality effect. Fig. 9 shows the CHF result for inlet quality effect under 30 and 60 ° conditions at atmospheric condition.

At both inclination angle conditions, '–0.003' of inlet quality is preheater off condition, and it means the quality value just depends on the inlet subcooling of flow. The quality is still negative value, even if the preheater is in the operating condition, because the calculated quality is global value in the flow. However, there would be the vapor generation just near the preheater surface, since the flow subcooling was just 2 K.

From the experimental result, it is shown that the CHF value increased with inlet quality increasing. Additionally, from the 60 ° result, the CHF does not proportionally increase with inlet quality. The CHF just jumped up when the preheater was operated, and it had almost constant trend. In other words, the vapor generated from the preheater is dominant effect on the CHF rather than the inlet quality near the nearly saturated condition. In addition, magnitude of the amount of vapor is not significant.



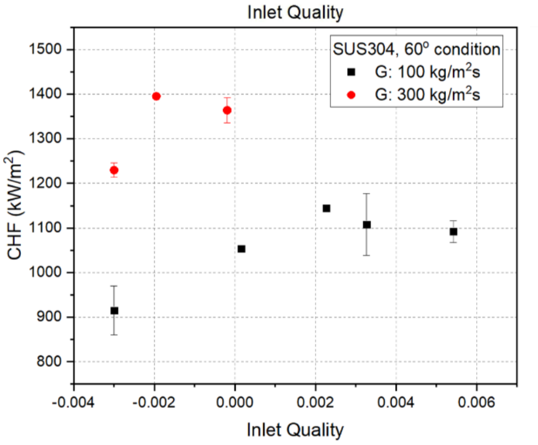


Fig. 9. Effect of inlet quality on the CHF (top: 30 ° angle condition, bottom: 60 ° angle condition)

If the flow is under fully subcooled condition, most of generated valor is condensed. Hence, the vapor cannot make any hydraulic effect (ex.: mixing and disturbing the flow near the main heater surface). However, near saturated condition, the vapor does not be condensed, and it can enhance the CHF value. Because the hydraulic effect of vapor has positive role to increase the CHF value.

3. Conclusions

In this research, the CHF experiments were conducted to produce the CHF database and to figure out some parameters' effect on the CHF. The inclination angle, pressure and inlet quality were considered for experiments. In case of the inclination angle and pressure, the higher angle and pressure made the enhanced CHF value. In case of the inlet quality, the CHF value shows the opposite result from the common sense. It is considered for explain this results that the hydraulic effect of vapor is dominant factor rather than thermal effect of it near the saturated condition.

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