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Measurement of Critical Heat Flux in Narrow Gap with Two-Dimensional Slices

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Abstract

A cooling mechanism due to boiling in a gap between the debris crust and the reactor pressure vessel (RPV) wall was proposed for the TMI-2 reactor accident analysis. If there is enough heat transfer through the gap to cool the outer surface of the debris and the inner surface of the wall, the RPV wall may preserve its integrity during a severe core melt accident. If the heat removal through gap cooling relative to the counter-current flow limitation (CCFL) is pronounced, the safety margin of the reactor can be far greater than what had been previously known in the severe accident management arena. Should a severe accident take place, the RPV integrity will be maintained because of the inherent nature of degraded core coolability inside the lower head due to boiling in a narrow gap between the debris crust and the RPV wall. As a defense-in-depth measure, the heat removal capability by gap cooling coupled with external cooling can be examined for the Korean Standard Nuclear Power Plant (KSNPP) and the Advanced Power Reactor 1400MWe (APR1400) in light of the TMI-2 vessel survival. A number of studies were carried out to investigate the complex heat transfer mechanisms for the debris cooling in the lower plenum. However, these heat transfer mechanisms have not been clearly understood yet. The CHFG (Critical Heat Flux in Gap) experiments at KAERI were carried out to develop the critical heat flux (CHF) correlation in a hemispherical gap, which is the upper limit of the heat transfer. According to the CHFG experiments performed with a pool boiling condition, the CHF in a parallel gap was reduced by 1/30 compared with the value measured in the open pool boiling condition. The correlation developed from the CHFG experiment is based on the fact that the CHF in a hemispherical gap is governed by the CCFL and a Kutateladze type CCFL parameter correlates CCFL data well in hemispherical gap geometry. However, the results of the CHFG experiments appear to be limited in their value because the power of the heaters was restricted by the three-dimensional (3D) geometry. The two-dimensional (2D) geometry relative to the 3D geometry enables the heaters to produce higher power. Experiments were conducted to develop the CHF correlation for gap cooling with the 2D slices. The experimental facility consisted of a heater, a pressure vessel, a heat exchanger and the pressure and temperature measurement system. Tests were carried out in the pressure range of 0.1 to 1 MPa for the gap sizes of 1mm and 2mm using demineralized water.

1. Introduction

Recent analysis of the TMI-2 reactor accident in 1979 suggested that additional cooling mechanisms not previously considered were present when the core melt relocated to form a continuous solid or partially molten phase in a water-filled lower plenum of the reactor pressure vessel (RPV) [1]. A cooling mechanism due to boiling in a gap between the debris crust and the RPV wall was proposed for the TMI-2 reactor accident analysis. [2, 3, 4, 5] If there is enough heat transfer through the gap to cool the outer surface of the debris and the inner surface of the wall, the RPV wall may preserve its integrity during a severe core melt accident.

In preliminary LAVA experiments performed at the Korea Atomic Energy Research Institute (KAERI), the influence of internal pressure load on the lower head vessel wall and the materials of the simulant melt on gap formation was investigated [6]. In parallel, VISU experiments at KAERI demonstrated that the heat transfer through the gap was related to the counter-current flow limitation (CCFL) [7]. While relevant experiments are being carried out in the U.S.[8] and Japan [9] as well as in Korea to understand the baseline heat transfer mechanism through the multidimensional gap, the databank is quite limited and mechanistic predictive tools are yet to be developed. On the other hand, external cooling of the RPV has drawn more attention than the complicated in-vessel cooling or gap-cooling. [10, 11] At the Seoul National University, as an advanced in-vessel design concept, the COASIS (COrium Attack Syndrome Immunization Structure) is being developed as a prospective in-vessel retention device for a next-generation LWR in concert with existing ex-vessel management measures.

If the heat removal through gap cooling is pronounced, the safety margin of the reactor can be far greater than what had been previously known in the severe accident management arena. Should a severe accident take place, the RPV integrity will be maintained because of the inherent nature of degraded core coolability inside the lower head due to boiling in a narrow gap between the debris crust and the RPV wall. As a defense-in-depth measure, heat removal capability by gap cooling coupled with external cooling can be examined for the Korean Standard Nuclear Power Plants (KSNPP) and the Advanced Power Reactor 1400MWe (APR1400) in light of the TMI-2 vessel survival.

Until now there have been no experimental data for gap cooling in the hemispherical vessel geometry exception CHFG experiments [12] and few studies on the critical heat flux (CHF) of the two-phase flow with narrow gaps, especially with the hemispherical gap geometry.

2. Theoretical Background

Since the gap size is of millimeter order, cooling mechanism through the narrow gap between the debris crust and the RPV will most likely be governed by CCFL or dryout. Therefore, it is important to identify the CCFL and dryout characteristics in the narrow gap. Previous CCFL work included studies for inlet entrance, inclined channel, gap effects, and so forth. However, the CCFL correlation applicable to the annular gap in the hemispherical geometry filled with debris is nonexistent.

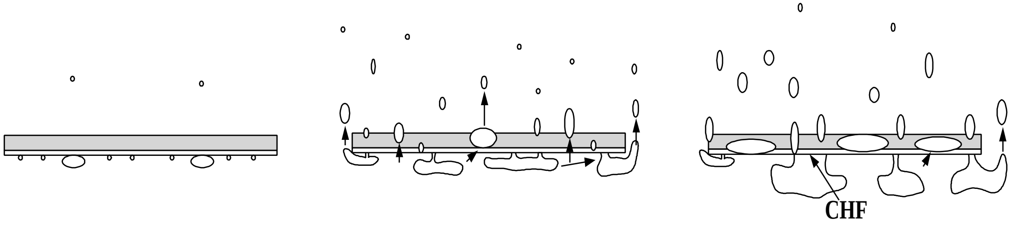
Although a great deal of studies on CHF were carried out during the last decade, an exact theory of the CHF has not yet been formulated. Since the CHF is a very complicated phenomenon, it is practically impossible to theorize exact model capable of explaining the detailed mechanism of the CHF completely. However, there are two models that are useful in explaining the CHF phenomenon. Two such primary models of the CHF have been put forward in the last decade: the hydrodynamic instability model [13] and the macrolayer dryout model. [14] The CHF is a critical phenomenon in nucleate boiling involving the dryout of liquid on a heated surface. It represents the upper bound of the excellent state of boiling where the heating surface is wetted with liquid and the heat transferred to the liquid is absorbed by the latent heat of vaporization in the immediate vicinity of the heating surface.

Widely accepted hydrodynamic CHF models have been developed by Zuber for upward-facing surface heating. The CHF for upward-facing surface is determined by the balance between the vapor generation rate and the critical vapor escape rate. The well-known CHF correlation for the case of conventional pool boiling on upward-facing heating is given below.

$$q_{CHF} = C\, r_G H_{fg} \left\{ \frac{s\ (r_L - r_G)}{r_G^{2}} \right\} \tag{1}$$

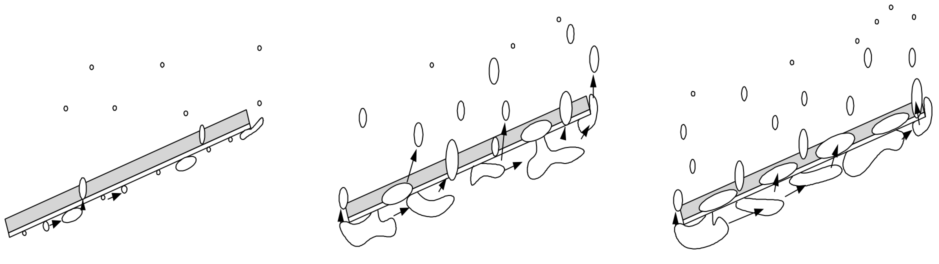
where C=0.131 [13].

However, the CHF mechanism for a hemispherical geometry in the present study is different from upward facing surface heating. For the downward-facing boiling on the surface of a heated hemispherical debris in this study, the buoyancy force and the surface tension force that act upon the vapor bubbles are not opposing to one another. Fig. 1 [15] shows the conceptual sketches of the bubble behavior with differing heating methods.



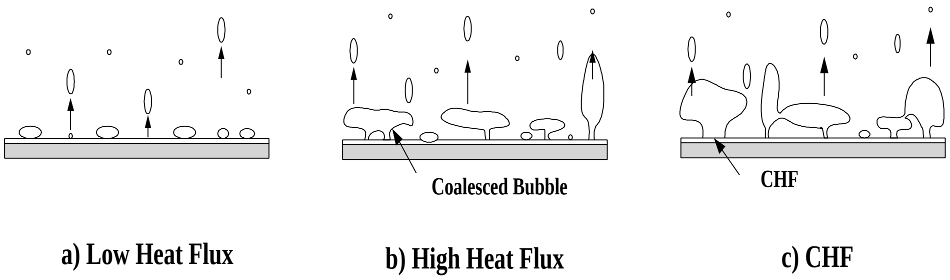
a) Low Heat Flux **b) High Heat Flux** **c) CHF**

(a) Bubble behavior with downward-facing heating



a) Low Heat Flux **b) High Heat Flux** **c) CHF**

(b) Bubble behavior with inclined downward-facing heating



(c) Bubble behavior with upward-facing heating

Fig. 1 Conceptual sketches of the bubble behavior with different heating methods

Cheung [11] intended to establish a proper scaling law and develop a design correlation for prediction of the CHF on the external surface of a large hemispherical vessel. A theoretical model was developed to predict the CHF limit for a saturated pool boiling on the outer surface of a heated hemispherical vessel. The model considers the existence of a microlayer underneath an elongated vapor slug on a downward-facing curved heating surfaces. Since the thickness of the two-phase boundary laryer in the external cooling case is nearly of centimeter order, Cheung's model may not properly be applied to the cooling within the hemispherical gap in the range of millimeters. In the CHF experiments for the hemispherical narrow gaps and visualization experiments in the same geometry performed at KAERI, CCFL occurred at the top end of the gap and prevented water from penetrating the gap. That is, CCFL brought about local dryout and finally, CHF in hemispherical narrow gaps. [12] When top flooding occurs in a hemispherical narrow gap, the maximum heat removal capability can be determined.

The CHF studies were also carried out in various gap geometries. Sudo and Kaminaga [16] and Katto and Kosho [17] performed the CHF experiments in gaps of rectangular channels and horizontal plates, respectively. Chang and Yao [18] carried out the CHF experiments with test sections of vertical annuls. Monde et al. [19] carried out an experimental study of the CHF at 1 bar in vertical rectangular channels. Three different heating surfaces were used and the gap size varied from 0.45 to 7.0 mm.

The results of ULPU-2000 [10, 20] experiment showed that the CHF was influenced by the angle.

In this study, the CHF mechanism is assumed to be influenced by two factors: 1) the CCFL at the upper portion, and 2) the downward facing heating at the lower portion. Fig. 2 schematically shows how the CHF mechanism may be interpreted from the experimental observation.

3. Experimental Apparatus and Conditions

If the CHF phenomena are experimentally studied with azimuthal angle dependency, the complicated enough heat removal mechanism in the narrow gap can physically be understood. A series of experimental investigations of the cooling mechanism in the narrow gaps, focusing on the CHF, were carried out. Fig. 3 shows the two-dimensional (2D) slice experimental facility, which consists of a rod heater, a heat exchanger and a coolant control system.

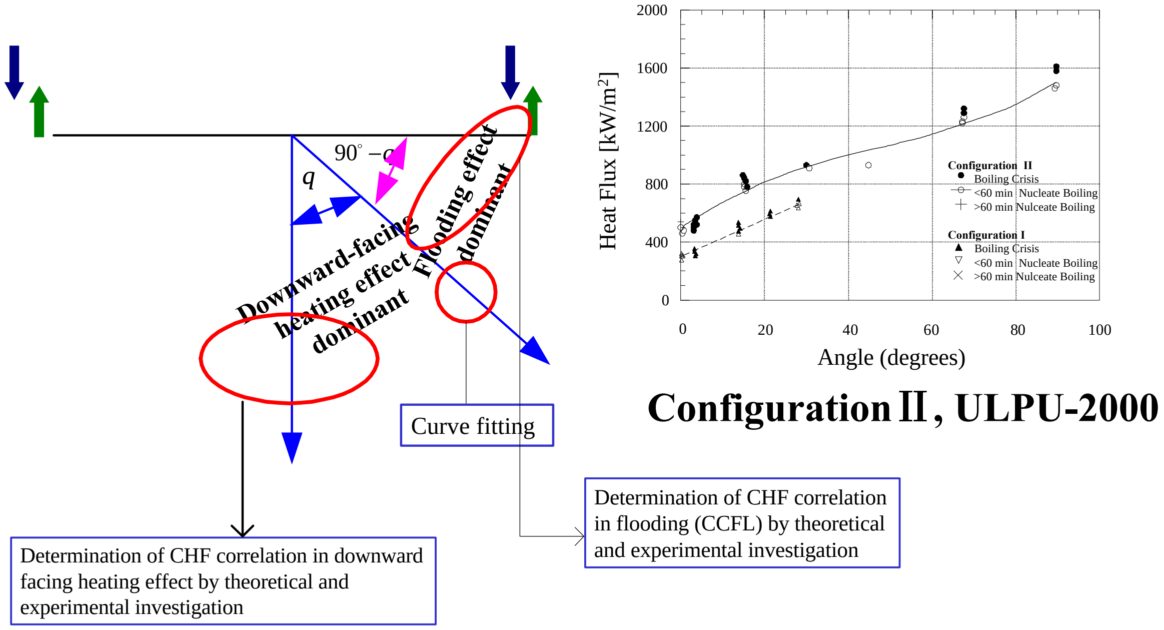


Fig. 2 Analytical model for the CHF mechanism

The principal operating characteristics of the experiment loop used are:

Thermal Power	Maximum 54 kW
Operating pressure	0.1 ~ 0.5 MPa
Test section geometry	Gap size : 1, 2mm, width : 100mm
Radius of copper	250mm
Boiling method	Pool boiling

The boiling experiment was designed in a closed at elevated pressures. The stainless steel pressure vessel was manufactured to provide the gap sizes of 1mm and 2mm between the copper shell and the pressure vessel itself. The experiment was performed using de-mineralized water. The heat generated by the rod heaters was removed in a heat exchanger. The heat exchanger functioned as system pressure regulator as well.

As the experimental facility consists of a closed loop, the first step necessary to run the experiments is to purge the air accumulated in the experimental loop. The air trapped in the closed loop will tend to deteriorate the heat transfer in the heat exchanger so that the water circulation may be slowed down. Initially the heater power is maintained at a low level and the pressure is then set at a pre-determined value. All the temperature readings are processed by a data acquisition system and carefully observed. If the temperature readings are believed to reach a quasi-steady state, the heater power is increased in a step-wise manner. When all the temperature readings increase monotonically, the heater power is cut off. The heat flux measurements were taken at different power levels with the rod heater power increased in steps, allowing for steady state to be achieved before measurements were done. The power was increased until temperature rapidly increased. The CHF was calculated from the input power of rod heaters just before the boiling crisis.

Fig. 4 shows a diagram of the installed thermocouples in test section.

In order to determine the local wall flux and the wall temperature, thirty-eight Type-K thermocouples were inserted at eighteen locations along the heating surface as illustrated in Fig.4. At each location, the thermocouple beads were epoxied into small holes which were precisely drilled with respect to each other and the heated wall.

The CHF was defined as the largest steady-state flux attained during testing. At the CHF, vapor covered the surface essentially insulating it. Consequently, heat supplied by the cartridge heaters could not be removed by the liquid and remained in the copper to cause a temperature rise and gradient decrease. Therefore, the CHF was detected during testing by an unsteady increase in the wall temperature accompanied by a sudden decrease in the wall flux.

4. Results and Discussion

For each experimental run to obtain the value of the CHF, the temperature curve was obtained. Fig. 5 and Fig. 6 show the temperature curves for the system pressures of 0.2MPa and 0.3MPa, respectively.

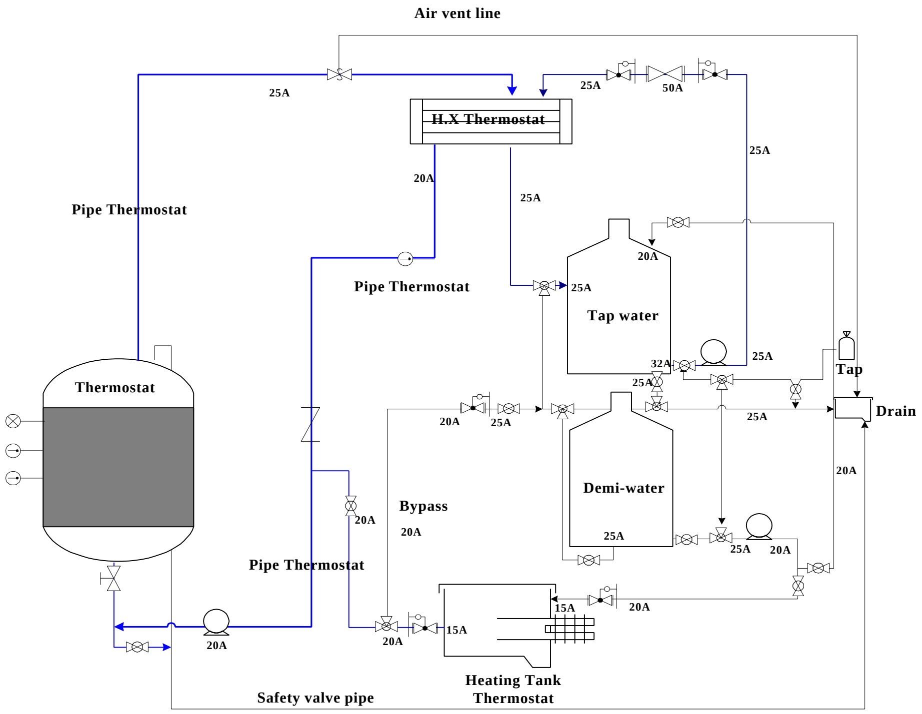


Fig. 3 Test loop schematic diagram

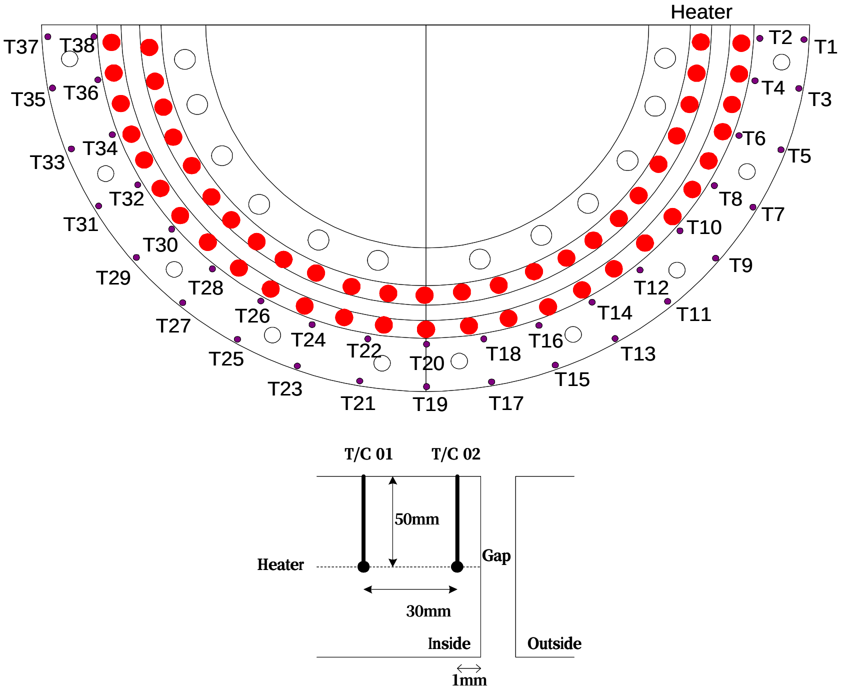


Fig.4 Thermocouples installation

Fig. 5(a) and 6(a) show that the temperature at the bottom is lower than at the upper region in the steady-state condition prior to the CHF. At the CHF, Fig. 5(b) and Fig. 6(b) show that the temperature at the bottom is rapidly increased. After the temperature at the bottom is increased, the temperature at the upper region is successively increased.

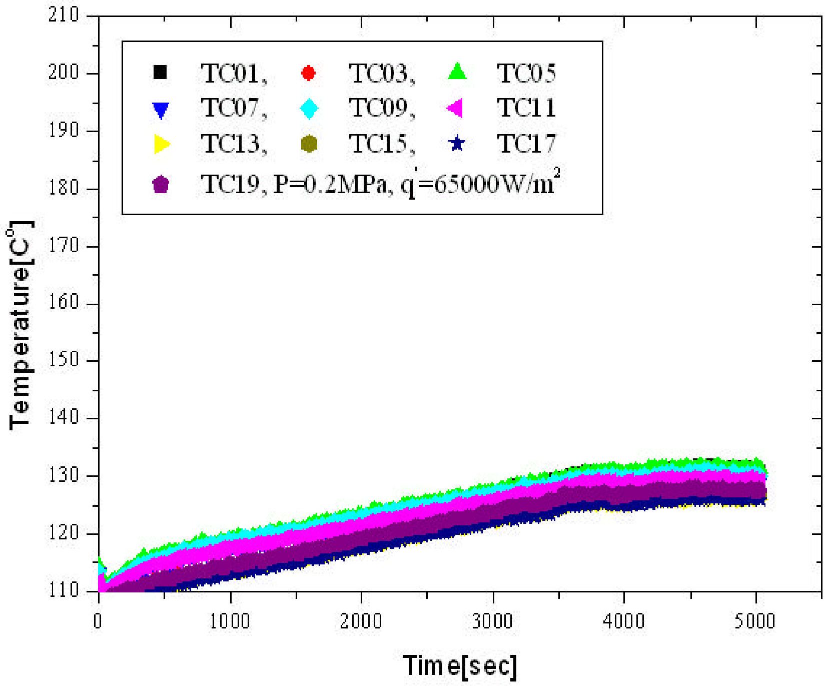
In this study, the temperatures are observed to increase successively from the bottom to the top region in all the cases. Hence, the mechanism of the CHF for the 2D slice narrow gap is due to global dryout.

It was mentioned in the previous section that the CHF mechanism was assumed to be influenced by two factors: 1) the CCFL in the upper portion, and 2) the downward facing heating in the lower portion. The increasing temperature in the bottom region is due to dryout by downward facing heating. Although the local dryout occurred in this study, the local dryout did not result from the CCFL, but rather from downward facing heating. However, in the CHFG test, a CCFL brings about local dryout and finally, global dryout in the hemispherical narrow gaps. Increase in the gap size leads to increase in the critical power.

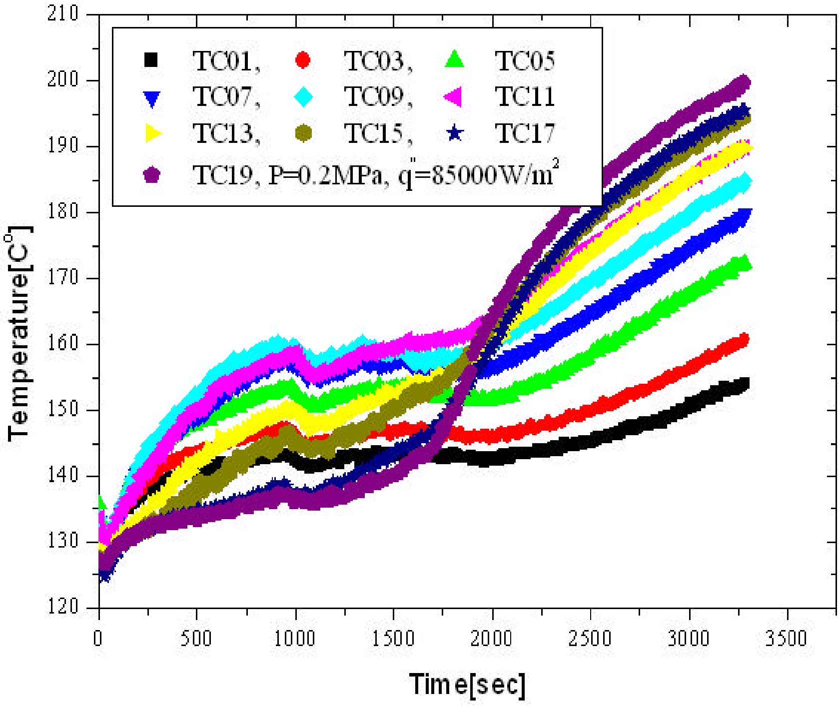
Fig. 7 compares the 2D slice data obtained in this study with the 3D hemispherical geometry data reported from KAERI. Also, Table 1 shows the values of critical heat flux in gap size 1mm, 2mm.

5. Conclusion

Boiling heat transfer experiments were conducted in the 2D narrow gap as a first stage to investigate the inherent cooling mechanism in a narrow gap.

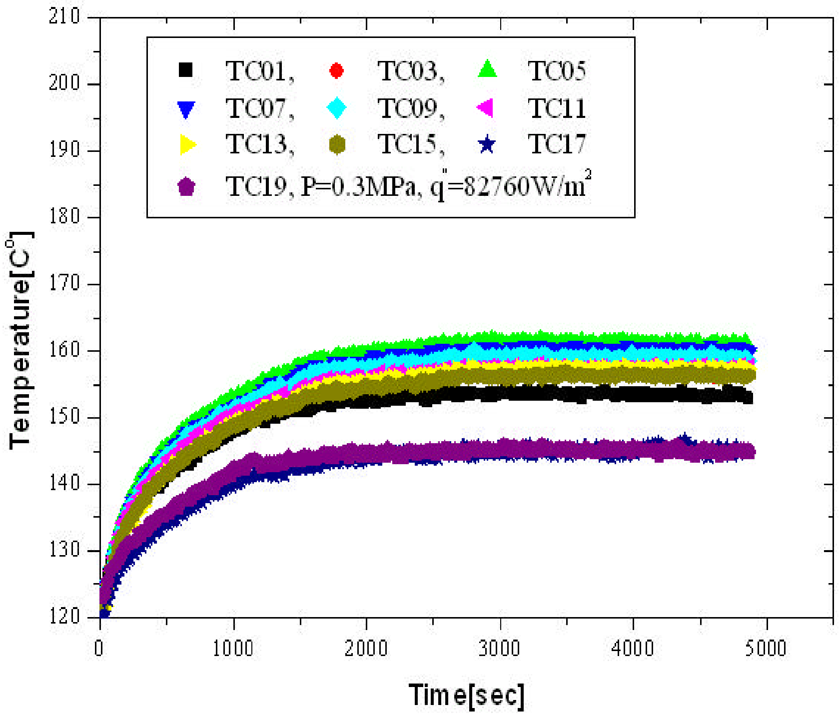


(a) Temperature behavior in steady state

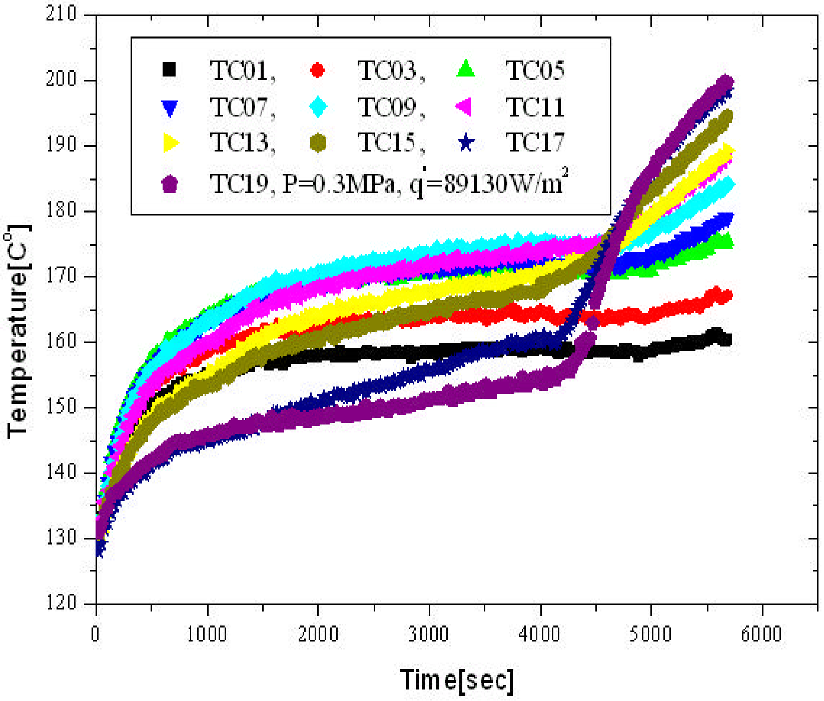


(b) Temperature behavior at the CHF

Fig.5 Temperature behavior at P=0.2MPa



(a) Temperature behavior for the steady state



(b) Temperature behavior at the CHF

Fig.6 Temperature behavior at P=0.3MPa

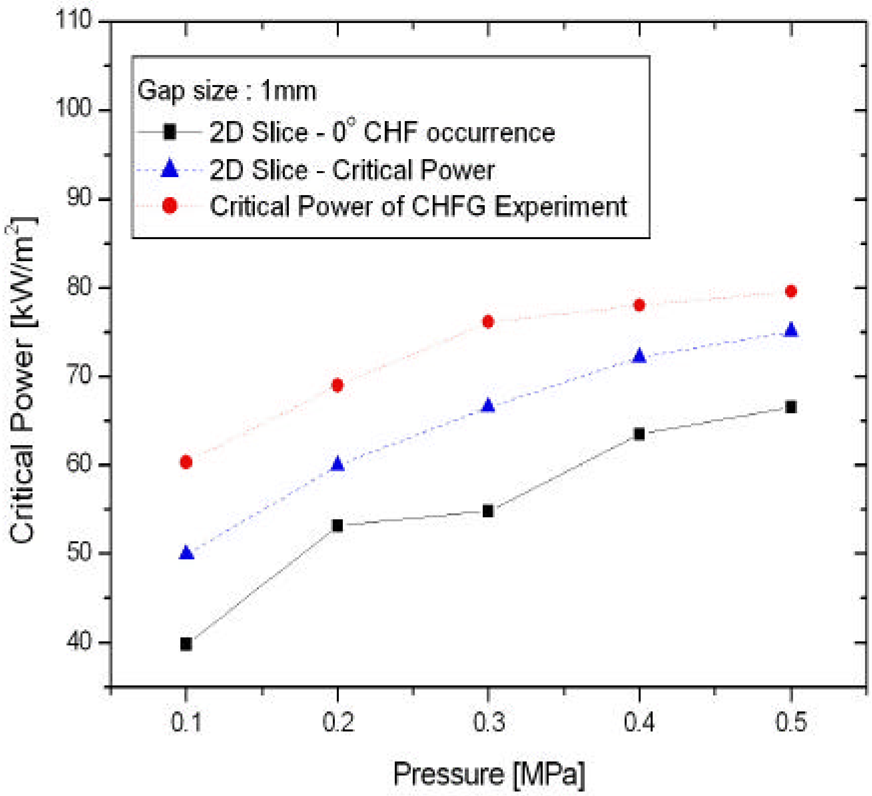


Fig.7. Comparison between 2D slice and 3D data for the critical power

In the CHF experiments for the hemispherical narrow gaps and visualization experiments performed at KAERI, the CCFL occurred at the top end of the gap and prevented water from penetrating the gap. That is, the CCFL brought about local dryout and finally, the CHF in hemispherical narrow gaps.

However, the starting point of the CHF in the 2D slice experiment differed from the results of the 3D CHFG. The CHF took place at the bottom earlier than at the top. Hence, the mechanism of the CHF in the 2D geometry with the narrow gaps is not the CCFL, but rather the dryout. The overall CHF(Critical Power) in this study is less than the overall critical power in the CHFG experiment. (About 80~90%) The bubble size of downward-facing heating is more than of upward-facing heating. The flow limitation is occurred due to transition from bubbly flow to slug and plug flow in point of view flow pattern. The increasing temperature in the bottom region is due to dryout. The reason is that the coalescence and departure between isolated bubble and slug by downward facing heating is not sufficiently achieved.

Nomenclature

H_{fg}	Latent heat of vaporization
P	Pressure
q_{CHF}	Critical heat flux
ρ_L	Density of liquid
ρ_G	Density of vapor

σ	Surface tension

Table 1. Values of critical heat flux in gap sizes 1mm and 2mm

1mm-gap				
	CHF(Start)		CHF(End)	
Pressure	Current (mA)	Heat Flux (W/m^2)	Current (mA)	Heat Flux (W/m^2)
1atm	5.30	39,874	5.50	49,957
2atm	5.60	53,164	5.80	59,978
3atm	5.70	54,832	6.00	66,592
4atm	5.90	63,498	6.10	72,171
5atm	6.00	66,592	6.20	75,134

2mm-gap				
	CHF(Start)		CHF(End)	
Pressure	Current (mA)	Heat Flux (W/m^2)	Current (mA)	Heat Flux (W/m^2)
1atm	6.00	62,592	6.30	74,978
2atm	6.40	79,402	6.60	86,675
3atm	6.70	89,951	7.20	110,063
4atm	7.00	101,719	7.60	N/A

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