The Effect of Gap Size to CCFL in Rectangular Narrow Channel for Double Heated Chase

Mulya Juarsa[1,2], Nandy Putra[1], Raldi Artono Koestoer[1],
Anhar Riza Antariksawan[2],

[1]Heat Transfer Laboratory Department of Mechanical Engineering,
Engineering Faculty, Universitas Indonesia
Kampus Baru UI Depok

[2]Thermal Hydraulics Experimental Laboratory
Center for Reactor Technology and Nuclear Safety, National Nuclear Indonesia Agency,
Kawasan PUSPIPTEK Serpong, Tangerang 15310
Email: juars@batan.go.id

Abstract

Many thermal hydraulics phenomena have been observed in various engineering application processes associated with the safety of nuclear power plants, especially in light water reactors. The accident at Three Mile Island Unit 2 (TMI-2) in the pressurized water reactor (PWR) in 1979, contributed to improvements in reactor design and safety based on subsequent research in thermal hydraulics and thermal management. In the event of a severe accident at TMI-2, the integrity of the reactor pressure vessel (RPV) was maintained, although part of the reactor core was affected by meltdown. However, cooling investigations in the gap between the debris and the RPV wall, which involved cooling heat transfer mechanisms in both reactors, have become important. Some thermal hydraulics parameters that are important to thermal management during the cooling process are heat flux, transient temperature and pressure, and cooling flow related to the cross-flow geometry. The Effect of gap size to counter current flow limitation (CCFL) in vertical rectangular channel was studied from results of experiment. Experiment was be conducted by using two vertical plate with 1 mm, 2 mm, and 3 mm narrow gap. The initial temperature of plate was decided at 600^{o}C. Debit and temperature of cooling water were controlled respectively about 0.09 L/s and subcooled temperature about 90^{o}C. The result shows that some methods can be used to know the existence of CCFL in the vertical rectangular narrow channels. The deviations for average velocity of water in non-heated and heated conditions for gap sizes 1 mm, 2 mm, and 3 mm were 67.5%, 71.7%, and 77.1%, respectively. From all the methods are concluded that the smaller gap size, the stronger CCFL effect. The superficial velocity of non-dimensional vapor was 43 times greater than the superficial velocity of non-dimensional water, indicating the presence of CCFL.

Keywords: rectangular, cooling rate, superficial velocity, rewetting time, CCFL

Introduction

The accident at Three Mile Island Unit 2 (TMI-2) in the pressurized water reactor (PWR) in 1979, contributed to improvements in reactor design and safety based on subsequent research in thermal hydraulics and thermal management. In the event of a severe accident at TMI-2, the integrity of the reactor pressure vessel (RPV) was maintained, although part of the reactor core was affected by meltdown. This situation may be similar to the severe accident associated with the boiling water reactor (BWR) at Fukushima Daiichi on March 11, 2011, in which the RPV was damaged and leakage was suspected. The mechanism of heat transfer between the debris and reactor vessel wall for TMI-2 differed from that of Fukushima Daiichi Unit-1 because of differences in the two reactor types. However, cooling investigations in the gap between the debris and the RPV wall, which involved cooling heat transfer mechanisms in both reactors, have become important. Some thermal hydraulics parameters that are important to thermal management during the cooling process are heat flux, transient temperature and pressure, and cooling flow related to the cross-flow geometry. **Ishibasi and Nishikawa (1969)** conducted an early study related to the characteristics of boiling heat transfer in narrow channels. In the research, limitations on the effects of saturation boiling heat transfer were reported. The authors noted that the boiling heat transfer in narrow channels had different effects, such as associated bubble characteristics; so, they categorized them as follows: for gap sizes greater than 2.0 mm, 0.5–2.0 mm, and less than 0.5 mm, bubble characteristics are a separated bubble area, coalesced bubbles, and almost no bubbles (dry area or vapor columns), respectively. Their study showed that, for a gap size below 0.5 mm, heat transfer occurred powerfully and was influenced by the insufficient availability of cooling water, a situation clearly caused by the effects of CCFL during cooling in the narrow channel between the debris and RPV walls. **Chang and Yao (1983)** also investigated CHF in a narrow channel for annulus geometry; with a closed bottom and variations of coolant and pressure, the proposed CHF correlations were based on the CCFL condition. **Mishima and Nishihara (1984, 1985)** performed adiabatic CCFL experiments on a single narrow rectangular channel using water at atmospheric pressure. In their experiments, gap sizes measured 1.5 mm, 2.4 mm, and 5.0 mm; the channel width was 40 mm for all cases. **Sudo and Kaminaga (1989)** conducted research concerning the characteristics of CHF based on CCFL correlation. The investigation was conducted with water as the cooling fluid, which flowed downward into a rectangular channel. The dimensions of the rectangular channels were 750 mm and 375 mm long, 50 mm wide, and 2.25 mm and 2.80 mm in gap size. Results indicated that the aspect ratio played an important role relative to CCFL and CHF characteristics. **Ghiaasiaan et al. (1994)** studied the CCFL phenomenon experimentally in an inclined round channel connected to bends at both ends. The velocities of working fluids (liquid) and superficial gas were 0.015–0.21 m/s and 0.1−3.1 m/s, respectively. The channel angle of inclination with respect to the vertical line was varied in the 0–60° range. **Kim et al. (2001)** studied and published visualization results of flow patterns and characteristics of CCFL using a vertical round tube with coiled wire. The collective opinion of **Murase et al. (2001),** based on data from other researchers, was that heat flux in a narrow annular channel was larger than in pool boiling because of the restricted flow area and the effect of CCFL.

Although many researchers have investigated boiling heat transfer in a narrow channel, discussions related to CCFL have not been conducted for investigations involving quenching. Therefore, the present study aimed to investigate the effect of the differences of narrow channel gap sizes on CCFL quenching under atmospheric pressure in single heated chases.

Experimental Methodology

Experimental apparatus

The experimental apparatus can be seen in **Figure 1**. The test section consisted of one heated plates made of SS316 stainless steel with dimensions of 8mm × 50mm × 1000mm as main plate. Outer heated plate was made by SS316 stainless steel plate with dimensions of 2mm × 50mm × 1000mm was utilized for visualization. Packing made of graphite was installed between those plates to form a narrow gap. The gap size varied based on the thickness of graphite. In our experiment, the variations of the gap sizes were 1.0 mm, 2.0 mm, and 3.0 mm. The width and the length of the channel were 50 mm and 1100 mm, respectively. Thus, the aspect ratios for width and gap size were 50, 25, and 16.7, respectively.

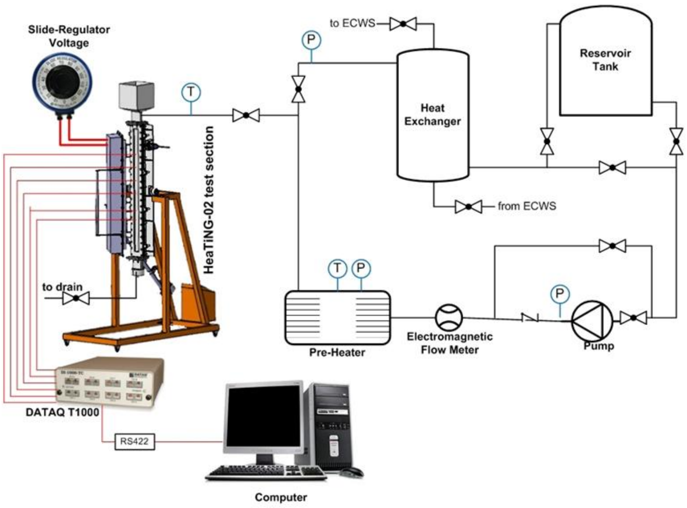

Figure 1 Experimental setup

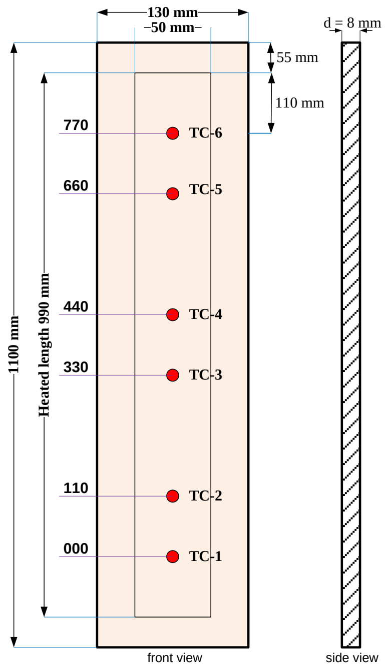

Figure 2 Thermocouple positions in main heated plate

Six type K thermocouples associated with 0.1^oC accuracy were installed in main plate to measure the temperature distribution along the main heated plate (shown in **Figure 2)**. Heater power is 12 kW with open-coil heater (manufactured by Kanthal) was installed and connected to 25 kW voltage regulators. To measure temperature distribution along the channel, the thermocouples were connected to a DATAQ T1000.

Experimental procedure

The channel gap size was set up in preparation for the experimental procedure. **Table 1** shows the experimental variables. Heating occurred due to radiation from the open-coil ceramic heater; the process was completed when the initial temperature reached approximately 600°C. Then, the heater was switched off and cooling water, with a 0.09 l/s mass flow rate and 90°C approximate temperature, flowed into the channel. This temperature was maintained and controlled with a thermal hydraulics mini-loop. After all temperatures on the main heated plate had nearly reached 90°C, experimentation was stopped. The first of two experimental processes was conducted to obtain experimental visualization of the boiling flow pattern inside the narrow rectangular channel during quenching. Quartz plates were used for visualization, and activity was captured using a high-speed video camera. The purpose of the second experimental process was to measure the change in temperature during quenching in the narrow rectangular channel. Results from the second process were used for boiling heat transfer analysis (i.e., calculating the change in heat flux during quenching based on heating from both sides).

Table 1 Experimental variables

Variable	Value
Gap size (mm)	1.0, 2.0, 3.0
Initial temperature (^oC) in the main plate	600
Cooling water volume rate (l/s)	0.09
Cooling water temperature (^oC)	90

Result and Disscussion

The indications of rewetting points are explained by the sudden increase in transient temperature histories observed as shown in **Figure 3.** Transient temperature during quenching is shown in the curve of time versus temperature only for TC6, based on the longer time for gap sizes 1 mm, 2 mm, and 3 mm. The curves showed that the smaller the gap size, the longer the required rewetting time due to the smaller water mass flow rate of vapor mass flow rate. For gap sizes of 2 mm and 3 mm, the rewet points occur at approximately the same time. The rewet point for 1 mm gap size occurred in 284 s at 302^oC. For gap sizes 2 mm and 3 mm, it occurred in 110.6 s at 334^oC, and 88.4 s and 371^oC, respectively. Sudden decreases in transient temperature occurred for gap sizes of 2 mm and 3 mm, indicating that the obstacle of the vapor did not last long enough to prevent water flow coming from above.

Rewetting time data was pointed our from **Figure 3** as hot condition, then compare it with cold condition data. **Table 2** shows that, for a gap size of 1 mm, the timing difference for water to exit a narrow rectangular channel between non-heated and heated conditions was 5.91 seconds. For the gap sizes of 2 mm and 3 mm, the time delay was 3.16 seconds and 2.70 seconds, respectively. The average rewetting velocity of water flowing inside the narrow rectangular channel was obtained from the channel length (1.1 m) divided by the time for water to flow through the rectangular channel during the heated condition.

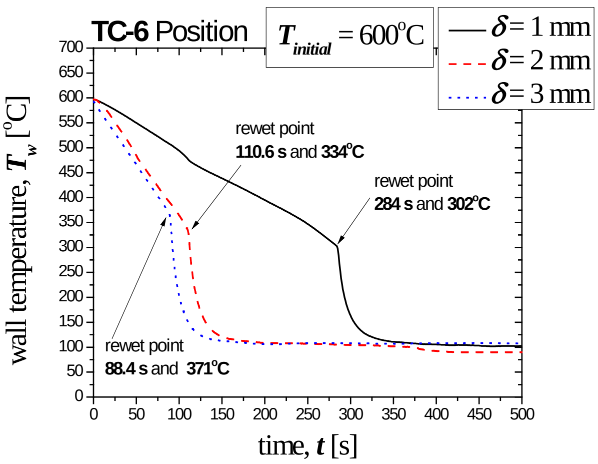

Figure 3 Rewetting time at each TC position for gap sizes 1 mm, 2 mm, and 3 mm

Table 2 Rewetting time for hot and cold conditions

T_{inital} (°C)	Gap size, δ (mm)	Time for water flow with non-heating (s)	Time for water flow with heating (s)
600	1.0	2.84	8.75
	2.0	1.25	4.41
	3.0	0.80	3.50

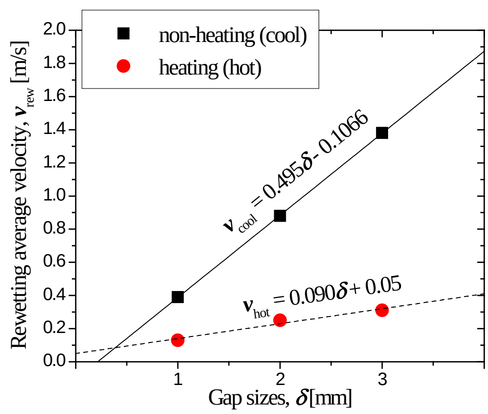

Figure 4 Average velocity of water inside rectangular narrow gap for hot and cold conditions

As comparation data from **Table 2** in **Figure 4** shows that the slope of the average velocity of water under the non-heated condition (v_{cool}) was greater than the average velocity of water for the heated condition (v_{heat}). The deviations for average velocity of water in non-heated and heated conditions for gap sizes 1 mm, 2 mm, and 3 mm were 67.5%, 71.7%, and 77.1%, respectively.

Counter Current Flow Limitation

Wallis (1981) correlation for superficial velocity can be explained from the countercurrent flow data represented and expressed as follows:

$$\left[j_g^*\right]^{1/2} + m\left[j_l^*\right]^{1/2} = C \qquad (1)$$

where

$$j_g^* = j_g\left[\frac{\rho_g}{g\Delta\rho D_h}\right]^{1/2} \quad \text{(gas/vapor)} \qquad (2)$$

$$j_l^* = j_l\left[\frac{\rho_l}{g\Delta\rho D_h}\right]^{1/2} \quad \text{(liquid/water)} \qquad (3)$$

When we solve equations 1, 2, and 3, then we find:

$$j_g = \frac{C^2\left[g\Delta\rho D_h\right]^{0.5}}{\left[\rho_g^{0.25} + m\rho_l^{0.25}\left[\frac{\rho_g}{\rho_l}\right]^{0.5}\right]^2} \qquad (4)$$

The superficial velocity of water (j_l) in CCFL will apply the average of rewetting velocity for water flowing inside a rectangular channel with flow variations based on changes in gap size. In our experiments, the constants ***m*** and ***C*** correlated in terms of the Bond number (B_o) and the aspect ratio of the geometry of the rectangular channel, respectively.

$$C = 0.66\left[\frac{w}{\delta}\right]^{0.25} \qquad (5)$$

$$m = 0.5 + 0.0015B_o^{0.333} \qquad (6)$$

where,

$$B_o = \frac{\delta w}{\lambda^2} \qquad (7)$$

$$\lambda = \left[\frac{\sigma}{g\Delta\rho}\right]^{0.5} \quad \text{Taylor wavelength} \qquad (8)$$

Figure 5 shows dimensionless superficial velocity taken for the experimental data for superficial velocity of water and the calculations based on data for superficial velocity of vapor. Dimensionless superficial velocity of vapor was calculated by solving Equations 1–8. If the superficial velocity of vapor is greater than the superficial velocity of water, then CCFL occurs in the channel. All gap sizes indicated the influence of CCFL during the cooling process inside the narrow rectangular channel. In the gap size of 1 mm, CCFL had the strongest effect because the value of j_g^* was the highest compared to other gap sizes.

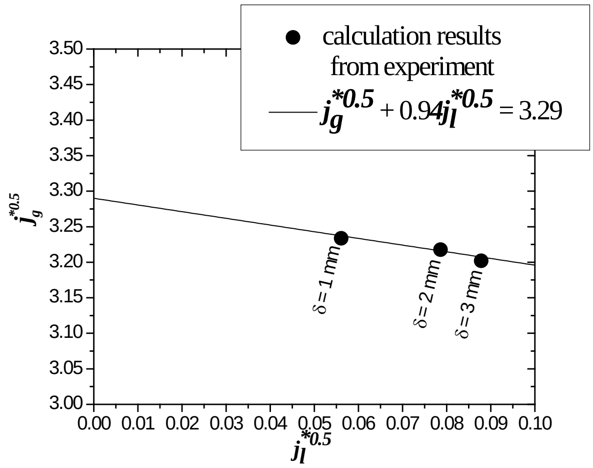

Figure 5 Dimensionless superficial velocity

Therefore**,** the larger the gap size, the smaller the CCFL effect. In this case, as j_l^* increased, j_g^* decreased. This event demonstrated the dominance of the CCFL effect in the rewetting process on the heated plate. Therefore, the smaller the gap size, the stronger the effect of CCFL between water and vapor in a vertical channel. For clarification, the average rewetting velocity of water that differs based on changes in gap size is referred to as the superficial velocity of water.

Conclusions

Various methods have been used to confirm the existence of CCFL in the narrow rectangular channels and. The average velocity of water based on an increasing channel gap size grew with a gradient of 0.09; therefore, this velocity was assumed to be the superficial velocity of water. Rewetting time occurred along the vertical positions of thermocouples in different patterns; rewetting time was similar for gap sizes 2 mm and 3 mm, in contrast with the 1 mm gap size. An increase in the amount of heat transferred from the heated plate through vapor into water was associated with an increase in the narrow gap size. The superficial velocity of non-dimensional vapor was 43 times greater than the superficial velocity of non-dimensional water, indicating the presence of CCFL. For the 2 mm gap size, the CHF increased about 29.12% compared to CHF in the 1 mm gap size; it increased about 77.30% for the gap size of 3 mm.

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Nomenclature

B_o	Bond number (-)
C	Wallis's constant (-)
g	Gravitational force (m/s^2)
j	Superficial velocity (m/s)
$j*$	Non-dimensional superficial velocity (-)
w	Plate width (mm)
v	Velocity (m/s)

Greek Letters

δ	Gap size (mm)
ρ	Density (kg/m^3)
$\Delta\rho$	Density differences (kg/m^3)
σ	Share force of fluids (N/m)
λ	Taylor wavelength (m)

Subscripts

g	Gas/steam
l	Liquid/water
sub	Subcooled
fg	Evaporation
cool	Non-heating case
hot	Heating case

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