Analysis of Critical Heat Flux on Boiling Curve in Vertical Rectangular Narrow Channel

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Abstract

Experiment about analysis of CHF in narrow channel was conducted by some researchers because it has important role to design an equipment in high heat flux. Therefor, this research was conducted to get the CHF based on position the thermocouple (upper, midle, and lower part of the plate). It is designed by using two vertical plate with initial temperature about 600^{o}C. It has main and cover plates stainless steel with 8 mm and 3 mm thickness, 1100 mm length, 50 mm width. Narrow gaps of the main and cover plates was set about 1.0 mm. Debit and temperature of cooling water are 0,09 lt/s and saturated temperature. As the results showed that the higher the initial temperature of plate, the higher the CHF and the higher the effect of environment properties, the smaller the CHF and also the highest CHF at the midle part of plate.

Keywords: CHF, narrow gap, and position of thermocouple.

1. INTRODUCTION

Critical heat flux (CHF) analysis is one of the complex analysis because it is affected by some variables that are gap sizes, geometry of channels (annulus, rectangular, cylinder), channel orientations (vertical, horizontal, inclined), heating types (single heated, bilateral heated), fluids test (water, refrigerant), pressure and temperature system, etc. In other hand, Katto (1994) say that CHF analysis was not only related to fluid dynamics, but also it is related to nonfluid dynamics movement of liquid to solid surface, and also the analysis associated with thermal aspect including intense liquid evaporation to heated surface. The understanding about CHF also important to design an equipment that related to high heat flux (Wright et al, 2008). Therefore, some researchers were experimentally conducting to analysis about CHF in narrow channel. The priority is scenario formed of narrow gap in severe accident nuclear reactor.

Experiments related to analysis CHF in narrow channel wre conducted by some researchers such as Sudo and Kaminaga (1989), Chang and Stan (1993), Xia et al (1996), Kien et al (2000), Zhang et al (2003), and Kuan and Kandlikar (2006). They were conducting an experimental study in vertical rectangular narrow gap with water as working fluid. It is heated from both sides and using 750 mm length, 50 mm width, and 2.25 mm gap size and also using 375 mm length, 50 mm width, and 2.80 mm gap size. The experiment was conducted to know CHF characteristic by comparing the prediction based on counter current flow limitation (CCFL) and CHF the experiment. The experimental result was indicating that aspect ratio has important role to CCFL and CHF characteristic for counter current flow. It is strongly implicating that CHF for downward flow is minimum in flooding condition on large inlet case and also when inlet water mass flux larger than in flooding condition for small water inlet case.

Chang and Stan (1993) was conducting experiment by using vertical rectangular alluminium heated from one side with 609.6 mm length, 50.8 mm width, and 1.98 mm gap size. The experiment was conducted in steady state, low flow and pressure condition for natural convection. The experimental results are downward flow have CHF 15% smaller than upward flow. Effect of subcooling for smaller than 44 K is not significant in rectangular narrow channel. If subcooling increases up to 66 K, the CHF increase of 15%. The experimental result of Xia et al (1996) was indicating that occurred decreasing mass flux caused by pressure drop before CHF. The experiment was conducted in natural convection condition by Freon R-113 as fluid test. Next, Kien et al (2000) was conducting an experimental study about boiling phenomena and CHF in micro gaps. It has been performed with annulus test section submerged in a pool of saturated water under atmospheric pressure. It is also set-up under the following condition: outer diameter of inner tube of 19 mm, heated length of 200 mm, gap sizes of 0.5-3.5 mm and inclination angles from horizontal to vertical positions. The experimental results reveal that the increase the CHF, the increase the gap size and the inclination angle.

Zhang et al (2003) was studying boiling curve in vertical annulus narrow channel heated from one side. The initial temperatures were variated from 500°C to 800°C and the gap sizes were changed from 0.5 mm to 7.0 mm. The results indicated that the heat transfer during cooling in the channel was significantly limited by the CCFL. Under the same initial temperature, if the smaller gap size, the longer rewetting time and the lower CHF. It is caused by existence of CCFL in the channel.

Kuan and Kandlikar (2006) was conducting research about the saturated flow boiling CHF in micro channels. It was investigated using water as the working fluid, and has six parallel micro channels with each having a cross sectional area of 1054 x 157 micrometer. The mass flow rate, inlet temperature of water, and electric current applied to heater are controlled to provide quantitative information near the CHF condition. The experimental results are the mass flux increase, the CHF increase. The vapor mass fraction at the micro channel outlet decrease with increase CHF.

From discussion above, most of experiments were conducted on a small length channel and also CHF analysed in narrow channel is so important to be conducted because it is related to safety of nuclear reactor. So, experiment to analysis CHF on a long plate based on part of plate that are upper, middle, and bottom part of plate need to be conducted. Hence, it is known the difference of CHF in each part of plate.

2. THEORETICAL

Heat Flux Calculation

Heat flux is heat rate transferred per area. Based on mean of heat flux, the heat flux in boiling curve is calculating by:

$$q = \rho . d . c . \frac{dT}{dt} \quad (1)$$

Correlation for comparing

a. CHF this experiment is compared by some correlations that known from previous research, that are:

Monde et. al (1982) correlation:

$$q_{CHF} = \frac{(0,16)h_{fg}\left[\frac{\sigma g \Delta\rho}{\rho_g^2}\right]^{0,25}}{1 + 6,7 \times 10^{-4}\left(\frac{\rho_l}{\rho_g}\right)^{0,6}\left(\frac{L_h}{\delta}\right)} \quad (2)$$

Xia et. al (1996) correlation:

$$q_{CHF} = \frac{\Delta h_{fg}\left[\sigma g(\rho_l - \rho_l)\rho_g^2\right]^{0,25}}{4,59 + 0,11\left(\frac{L_h}{\delta}\right)} \quad (3)$$

Leinhard (2001) correlation:

$$q_{CHF} = (0,149).\, h_{fg}.\, \rho_g^{1/2}\left[\sigma.\, g.\left(\rho_f - \rho_g\right)\right]^{1/4} \quad (4)$$

3. EXPERIMENTAL APPARATUS AND PROCEDURE

This experiment is a joint two facilities. They are Untai Uji Beta (UUB) and HeaTiNG-02 (see **Figure 1A**). UUB is used to set-up flow rate and temperature of cooling water before it is flowed to the channel. UUB has a centrifugal pump for setting-up flow rate of the cooling water and circulating it, flow meter is used to know mass flow rate of the cooling water, pre heater is used to increase the cooling water temperature, thermocouple is used to measure the temperature, and some of valves is used to open or close the cooling water flow. HeaTiNG-02 is the main test section. It has main and cover plates stainless steel with 8 mm and 3 mm thickness, 1100 mm length, 50 mm width. Narrow gaps of the main and cover plates was set about 1.0 mm. The main and cover plates have three chromel-allumel thermocouples (TC), the location can be seen at **Figure 1C**. It is used to measure of temperature during heating and cooling process. Figure 2 show the schematic apparatus.

WinDAQ T1000 Acquisition data is used to measure plate temperature during process with 1 data per second. Slide regulator with the 25 kW maximum power is used to change power input during heating process until the plate temperature is about 600°C. The power input was gradually increased in order to uniform temperature.

The experiment is started by setting up the gap size, then the plates are heated by ceramic heater until one of the TC have the initial temperature is about 600°C. If it has been reached, the ceramic heater is switched off, then 0.09 L/s and about 90°C of cooling water that controlled at UUB is flowed to the channel. If all of the temperatures are closing to 90°C, the experiment is stopped.

Tabel 1. Experimental variable

Variable	Value		
	I	II	III
TC location (mm from upper part)	165	495	825
Initial Temperature (°C)	600	600	600
Gap Size (mm)	01,00	01,00	01,00
Cooling water volume rate (L/s)	00,09	00,09	00,09
Cooling water temperature (°C)	90,00	90,00	90,00

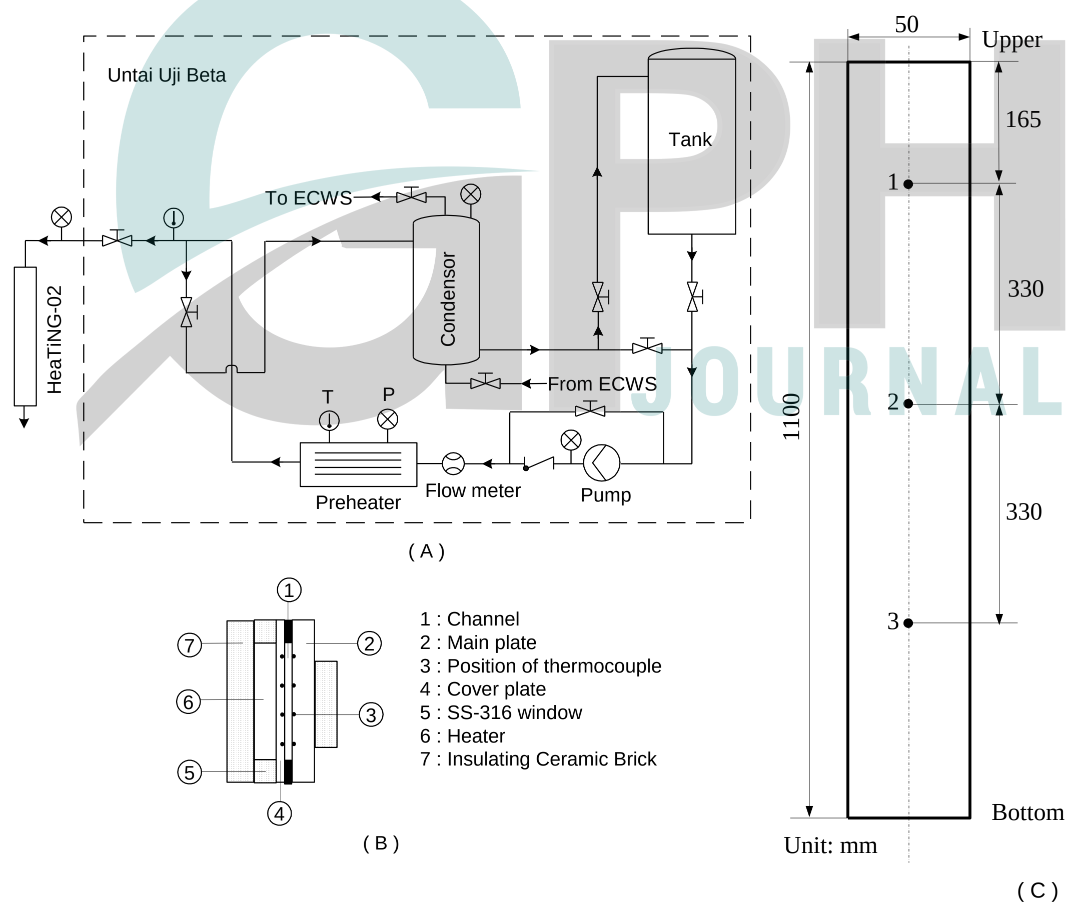

Figure 1. (A) Schematic apparatus, (B) Detail HeaTiNG-02, (C) Location of Thermocouple

4. RESULTS AND DISCUSSIONS

Transient Temperature

Transient temperature is the different temperature to the time. The temperature at each time will be captured by TC and then recorded by Data Aquisition System and finally it can be read at personal computer. The temperature in the plate was plotted as **Figure 1**. In the initial condition, temperature on midle part is highest than other, and temperature on upper and bottom part are lower than midle part, it is caused by in the bottom part is opened and in the upper part is not isolated, so the condition is effected by atmosfer that restricting the increasing of temperature on the part of plate.

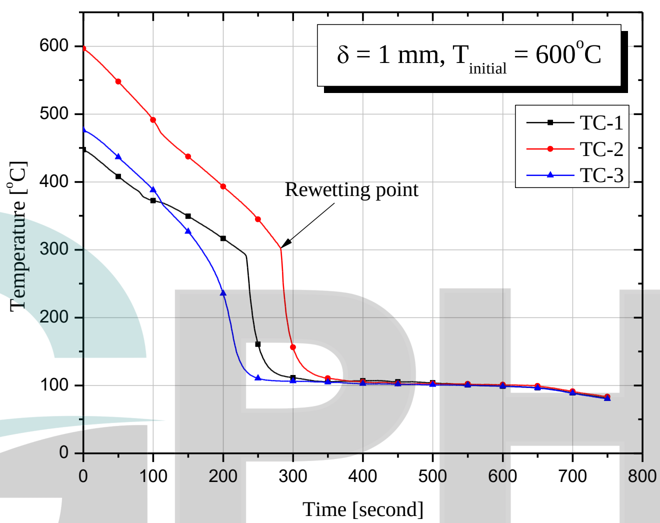

Figure 2. Transient temperature

In the initial condition also have not been occurred contact between water and plate surface because in the plate is existed by vapor blanket, the radiation heat transfer is occurred but the convection have not been occurred. It is caused by vapor blanket that have high pressure was restricting to contact the cooling water to surface plate. The first point to its contact is known as rewetting point and the time is known as rewetting time. In the rewetting point is starting point of heat transfer. From initial to rewetting point is known as film boiling regime. Next condition is drastically droping temperature. It is as indicator of rewetting point. After rewetting point, the convection heat tranfer is occurred, the decreasing of the temperature is not so drastic until the temperature is about 90°C. It is the finally of experiment.

Boiling Curve

Figure 3 is representing the relation of heat flux and ΔT_{excess} and usually called as boiling curve. Heat flux is heat transfer rate per area and ΔT_{excess} is a difference of temperature plat and temperature saturation of cooling water. Heat flux was calculated from transient temperature by equation 1 then plotted to figure 3. In the figure, it is indicating that all of the position TC have film boiling in the initial condition because the plate surface is contained by vapor blanket, so radiation heat transfer is more dominant than other. After boiling phenomena, it is called transition regime. The initial point to start the phenomenon is called Leidenfrost point. The point have the lowest of heat flux. Then, if the water contact to the plate surface, the temperature drastically drop. It is causing the large difference of plate temperature before and after contact. This condition is causing the very high heat flux. Next, the heat flux is decreasing until natural convection. From figure above, it is also known that TC-3 has the longer transition process than other. It is caused by the position of TC-3 is the lowest and influenced by atmospheric properties, so that the temperature is lower than other. The phonomenon in this research is called as cooling process because film boiling is the first condition, then transition, nucleat, and natural conditions. It different to Nukiyama curve (Nukiyama, 1934), the curve is heating process, natural convection is the first condition then nucleat boiling, transition and film boiling.

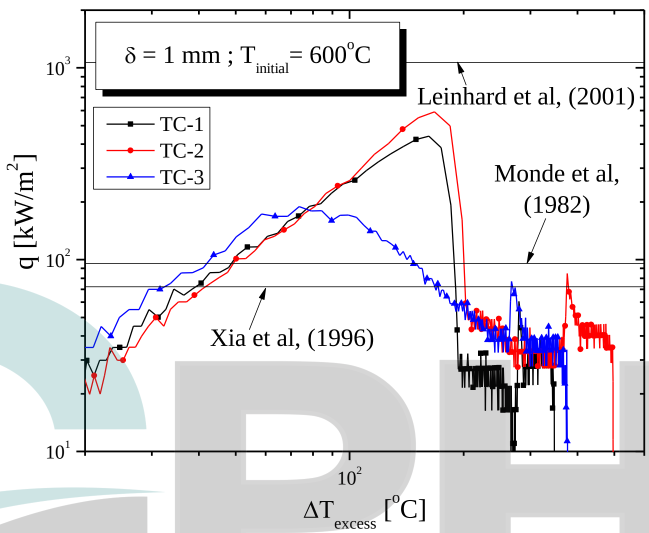

Figure 3. Boiling curve

Critical Heat flux

CHF is a indication of contact point of cooling water to surface plate. This condition is known by variety names: the burn out point, the peak heat flux, the boiling crisis, the DNB or Departure from Nucleat Boiling, and CHF or Critical Heat Flux. In this research, CHF can also as the last of boiling transition because the starting point of this research is reversed with the experiment of Nukiyama. CHF is a term more often used in flow boiling (Leinhard, 2001). It is as the critical point because it is the point of control condition. If the temperature is not controlled, so the condition will move to burn out and it is not passing to transition regime. So, the point is the most danger point in operating of heat exchanger with heat flux as independence variable like as nuclear reactor. In CHF point, the heat flux is high while the difference temperature is low and heat transfer coeffisien is high, and the point is the dangerest condition.

From the Fig. 3, it can be known that the highest CHF at midle part of the plate and the lowest at the lower part of it. The condition is related to the initial temperature. If the initial temperature is very high, so the CHF will high too. It is caused by difference temperature in the first contact between water and plate is very high, so it will give the high value of CHF.

For the comparing condition, CHF is compared to Monde et. al (1982) correlation. It is using vertical rectangular narrow channel with closed in the lower side. And also it is compared to Leinhard and Dhir (1973) correlation, it is conducted in pool boiling condition. It is also compared to Xia (1996), it is conducting the research by variating the length of vertical plate from 56 mm to 197 mm. For all comparation, Leinhard and Dhir (1973) correlation is closed to CHF point of TC-1 and TC-2. Monde et. al (1982) and Xia (1996) correlations is closed to TC-3.

So, Monde et. al (1982) and Xia (1996) correlations are suitable to lower initial temperatur and Leinhard and Dhir (1973) correlation is suitable to higher initial temperature of plate.

5. CONCLUSION

From the analysis above, it can be concluded that:

1. The higher the initial temperature of plate, the higher the CHF
2. The higher the effect of environment properties, the smaller the CHF
3. The highest CHF is at the midle part of plate.

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REFERENCES

Chang, H.OH., and Stan, B.E., 1993, Critical Heat Flux for Low Flow Boiling in Vertical Uniformly Heated Thin Rectangular Channels, International Journal Heat Mass Transfer, Vol. 36, No. 2, pp. 325-335.

Katto, Y (1994) Critical Heat Flux, Multiphase Flow Int. Journal, Vol 20, pp.53-90.

Kien S.H, Baek W.P, Chang S.H, 2000, Measurement of Critical Heat Flux for Narrow Annuli Submerged in Saturated Water, Nuclear Engineering and Design 199, pp.41-48.

Kuan W.K, Kandlikar S.G, 2006, Experimental Study on Saturated Flow Boiling Critical Heat Flux in Micro Channels, Proceeding of ICNMM 2006, june 19-21, Limerick, Ireland.

Lienhard, J.H., and Dhir, 2002, A Heat Transfer Textbook, Third edition, Phlogiston press.

Monde. M., Kusuda, H., and Uehara, H., 1982, Critical Heat Flux during Natural Convective Boiling in Vertical Rectangular Channel Submerged in Saturated Liquid, Trans. ASME, Vol.104, p.300-303.

Nukiyama, S, 1934, The maximum and minimum value of the heat Q transmitted from metal to boiling water under atmospheric pressure, int. J Heat Mass Transfer Vol. 9, pp 1419-1433

Sudo, Y., and Kaminaga, M., 1989, A CHF Characteristic for Downward flow in A Narrow Vertical Rectangular Channel Heated From Both Sides, International Journal Multiphase Flow, Vol. 15, No. 5, pp. 755-766.

Wright C.T., O'Brien J.E., Spall R.E., 2008, A new critical heat flux correlation for vertical water flow through multiple thin rectangular channels, International Journal of Heat and Mass Transfer, vol. 5, pp. 1071–1084.

Xia, C., Weilin, H., Zengyuan, G., 1996, Natural Convective Boiling in Vertical Rectangular Narrow Channals, Experimental Thermal and Fluid Science, Vol.12, p.313-324.

Zhang, J., Tanaka, F., Juarsa, M., Mishima, K., 2003, Calculation of Boiling Cuves during Rewetting of a Hot Vertical Narrow Channel, The 10th International Topical Meeting on Nuclear Reactor Thermal Hydraulics.