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STUDY ON BOILING PHENOMENA DURING HEAT TRANSFER IN BOTTOM REFLOODING SIMULATION EXPERIMENT

Mulya Juarsa, Puradwi I. W. and Anhar R. Antariksawan

Thermal-Hydraulics Laboratory
Center for Reactor Technology and Nuclear Safety
Indonesian – National Nuclear Energy Agency
PTRKN Building No.80 Kawasan PUSPIPTEK Serpong, Tangerang 15310 INDONESIA
Tel: (62)-21-7560912, Fax: (62)-21-7560913, Email: juars@batan.go.id

ABSTRACT

STUDY ON BOILING PHENOMENA DURING HEAT TRANSFER IN BOTTOM REFLOODING SIMULATION EKSPERIMENT. Study to understand boiling phenomena in bottom rewetting hot surface is an important step to analyze boiling heat transfer during flooding process in Post-LOCA event. Experimental apparatus QUEEN-II test section was designed, constructed and tested for quenching research on boiling heat transfer in bottom reflooding. The experiment has been done by heated-up SS316 rod up to 850^{o}C, and then cooling down by water at a temperature of 90^{o}C flowing from the bottom. The results of experiment showed that boiling regimes was quite different compare the previous experiment. Three different values of critical heat flux (CHF) base on boiling curve are 53.51 kW/m^2, 58.45 kW/m^2 and 67.31 kW/m^2 respectively indicating three differences of water mass flow rate of 0.015 kg/s, 0.060 kg/s and 0.140 kg/s respectively. The effect of 57% water mass flow rate increasing only increase 21% of CHF.

Keywords: boiling, reflooding, critical heat flux

ABSTRAK

STUDI FENOMENA PENDIDIHAN SELAMA PERPINDAHAN PANAS PADA EKSPERIMEN SIMULASI *BOOTOM REFLOODING*. Studi untuk memahami fenomena pendidihan yang terjadi selama pembasahan ulang dari bawah pada permukaan panas merupakan langkah penting dalam menganalisis perpindahan panas pendidihan yang terjadi selama proses flooding dalam peristiwa Post-LOCA. Peralatan eksperimen yang diberi nama bagian uji QUEEN-II telah didesain, dikonstruksi dan diuji untuk penelitian *quenchin*g pada perpindahan panas pendidihan selama *bottom reflooding*. Eksperimen dilakukan dengan memanaskan batang panas SS316 hingga mencapai temperatur awal 850^{o}C, kemudian didinginkan oleh air dengan temperatur 90^{o}C yang mengalir dari arah bawah. Hasil eksperimen menunjukkan bahwa rejim pendidihan agak berbeda dibandingkan dengan hasil eksperimen terdahulu. Tiga perbedaan nilai fluks kalor kritis (FKK) yang diperoleh berdasarkan kurva didih secara berturut-turut adalah 53.51 kW/m^2, 58.45 kW/m^2 and 67.31 kW/m^2 yang mengindikasikan tiga perbedaan laju aliran massa air 0.015 kg/detik, 0.060 kg/detik dan 0.140 kg/detik. Efek kenaikan laju aliran massa air sebesar 57% hanya menaikkan FKK sebesar 21%.

Kata kunci : pendidihan, *reflooding*, fluks kalor kritis

1. INTRODUCTION

Study on boiling heat transfer during bottom core reflooding, especially in PWR is an attractive research on nuclear engineering. This work is relates to core cooling process using ECCS on Loss of

Coolant Accident (LOCA). Then, the accident management must be placed to terminate the accident. This situation would be worst resulting on core melt down caused by anomaly on boiling heat transfer during reflooding process. In nuclear reactor accident, wetting hot cladding wall during ECCS injection has been studying since more than two decades, using experimental model or analytical model. X.C. Huang et al. [1] have been doing a quenching experiment using cylinder copper at pressure range between 1-10 bars and mass flux variations begin from 25 $kg.m^{-2}.s^{-1}$ until 150 $kg.m^{-2}.s^{-1}$. He analyzed boiling curve from heated rod temperature's data. L. Spood et al. [2] observed characteristics of temperature transient at heated rod simulating PWR fuel rod. W.J. Green and K.R. Lawther [3] using ACTOR Freon loop investigated transient heat transfer at low temperature on flow boiling regime. P.K. Das et al. [4] conducted some experiments to investigate rewetting phenomena on hot vertical annular channel, his research have a good result to be use in rewetting analysis purposes, even though it was not similar. Author [5] performed a preliminarily experiment using QUEEN-I test section to investigate heat transfer between heated rod outer surface and water during boiling process, but only for initial temperature 400°C, 500°C, and 600°C.

The thermal-hydraulics behavior of hot vertical rod cooling during bottom flooding process and heat transfer mechanisms encountered could be flow direction-dependent. Following the blow-down phase of LOCA, the clad temperature may rise quickly to a high value (around 930°C at PWR) [6], so that the injected ECCS may not wet the clad immediately on coming into contact. Rewetting the clad is essential for effective heat removal by the emergency coolant. Extensive studies on the rewetting of hot surface have been carried out. During cooling process for a given initial temperature along rod length, the rewetting velocity may be slow down for higher initial temperature. Thus, water mass flow rate also become one of the parameters to consider in the study on boiling phenomena for a given set of initial temperature condition. Further, a majority of the earlier studies on bottom flooding including rewetting study was covered a narrow range of coolant flow rates and initial surface temperature. Therefore, study on boiling heat transfer phenomena in high temperature (850°C) during bottom reflooding simulation experiment become an important work. Temperature and mass flow rate as parameters which involves on quenching event during Post-LOCA will be investigate. The present work is aimed to investigate boiling phenomena and heat transfer mechanisms using the value of CHF and related to mass flow rate in single rod using QUEEN-II test section which was connected to BETA thermal-hydraulics test loop.

2. EXPERIMENTAL SET-UP

2.1. QUEEN-II Test Section

The diagram of the experimental set up employed in the present work for quenching experiment in bottom flooding cooling is shown in Fig. 1 and Fig. 2. The set up of experimental apparatus mainly consists of a source of power supply (PS) using slide voltage regulator 25 kW, de-mineralized water supply (in reservoir tank), QUEEN-II test section and the data acquisition system (DAS) including computer as data recorder and monitoring. The QUEEN-II test section comprises a single stainless steel (SS 316) tube with 9.8 mm outer diameter and 7.4 mm inner diameter as a heated rod which is aimed to simulate a fuel cladding. Heated rod has 8 thermocouples which were installed in outer surface along 700 mm of heated rod length (see Fig. 3). A coil heater as heat source was installed in semi-cylindrical ceramic called as ceramics heater. Ceramic heater has a function to heat-up rod by radiation through quartz glass tube until designated initial temperature.

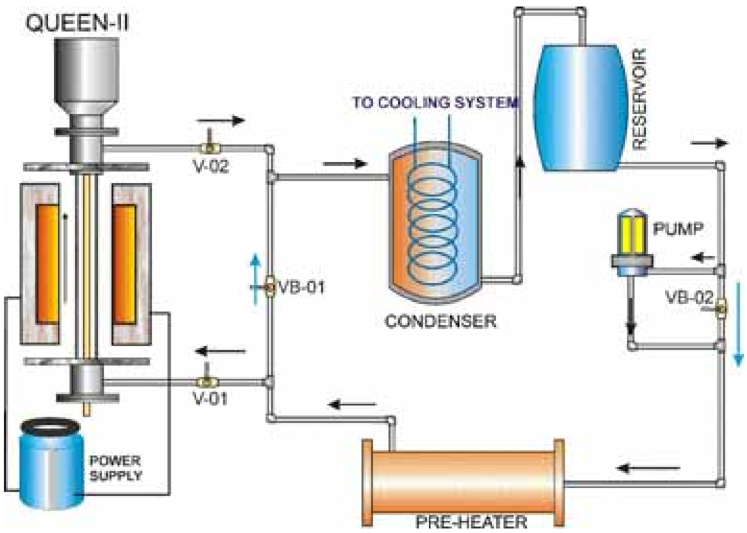

Figure 1. BETA loop flow diagram

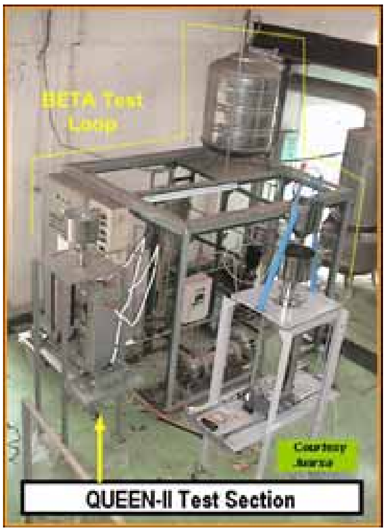

Figure 2. Experimental apparatus photograph

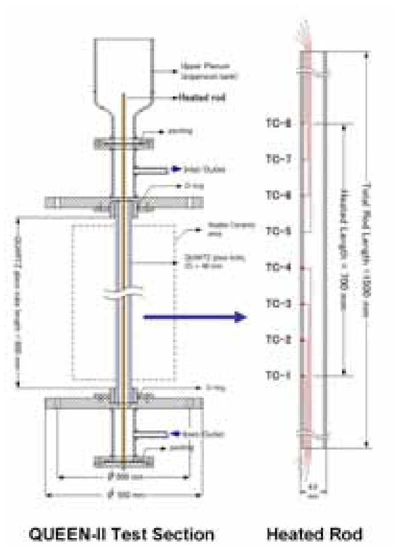

Figure 3. The QUEEN-II test section

Thermocouples signals are recorded

using data acquisition system (DAS) WinDAQ T1000 to a personal computer with sampling rate of 1 data per-second. Observation of the boiling heat transfer during cooling process is conducted using a digital video camera with recording rate 30 fps (NTSC system).

2.2. Experimental Procedure and Range of Parameters

Before starting the experiment, some test to determine water velocity in cold condition (without heating the heated rod) was conducted. The water mass flow rate was calculated using equation:

$$G = \frac{\pi}{4}(D^2{}_{in-glass} - d^2{}_{out-tube}) \times \rho_f \times v_{cold} \qquad (1)$$

Three variation of water mass flow rate are pointed out, from 0.015 kg/s, 0.060 kg/s until 0.140 kg/s, respectively.

The experiment is started when heated rod is heated up gradually until the initial temperature i.e. 850^{o}C achieved. After initial wall rod temperature is reached, the power supply is switched off. The experiment was conducted by opening the valve (V1) and letting water with temperature 90^{o}C to enter from the bottom into the top of quartz glass tube and flood the heated rod. Experiment was finished when the quartz glass tube had been completely flooded. Experiments were repeated with three different water flow rate.

3. RESULTS AND DISCCUSIONS

3.1. Cooling Process and Temperature Histories

The cooling process in the top part is different compare to the bottom part of the heated rod. Temperature profile at along vertical direction is almost similar with sinusoidal curve. This profile was occurred due to the direction conduction heat transfer from the bottom part of heated rod to flange area in bottom and from the top part of heated rod to flange area in the top part. It's also due to heat flux in the middle of ceramic heater during heating process is high. Fig. 4 shows the heated rod wall temperature histories during cooling process for water mass flow rate 0.015 kg/s, 0.060 kg/s and 0.140 kg/s respectively, for each TC point measurement. Due to temperature profile anomalies on TC1 and TC8, in Fig. 4 only shows temperature transient curve from 6 thermocouples (TC-2 to TC-7). The lower temperature measurements in TC1 and TC8 are lower than other TC. As consequences, the coolant rewets in the beginning of cooling process is slowly as shown, in TC2 and TC3 temperature drop is not sharp. But in the middle area of heated rod (TC4) temperature is decreasing sharply. Starting in the top part, direction from TC5 to TC7, temperature decreasing is not sharp.

Then, Fig. 4 shows from top to bottom of heated rod TC point from TC7 until TC, for three different coolant flow rate. Prior to the heated wall is rewetted by the coolant, the rod cooling is occurred through radiation process from the outer surface of rod wall to the air in quartz glass tube. In general, because the radiation heat flux is relatively small, the wall temperature was decreased slowly; the higher initial temperature, the faster temperature decreases as observed from temperature histories, due to higher radiation flux.

When the rewet point approached, the heated rod temperature begins to drop due to increased axial heat conduction along the heated rod. Then quenching started which lead to a rapid temperature drop, knowing as transition boiling process. After the surface was rewetted, as transition boiling, the heated rod was cooled down to bulk temperature quickly

At the point of TC-4, for all mass flow rate, temperature decreases occurred in drastically (indicated by arrow in Fig. 4), because it happened prior to the transition and nucleate boiling regime. Also this condition could be said, that in TC4 area film boiling is longer than another TC point. In Fig. 5, the photograph of cooling process at mass flow rate 0.140 kg/s (as example photos) shows there is complexity of boiling was occurred during boiling process. After passing TC4, the film boiling regime changed into un-stable film boiling, indicated by heavy boil.

From this observation, the pattern of boiling regime (from Fig.5A) could be explained in Fig. 6, it shows that there are two area of film boiling regime (beside nucleate and transition boiling), first area is quite film boiling area; this area has a stable film boiling. We can see, that water flow rate surrounding this area is not disturbed, and the length of Taylor instability is short. Above this area there is film boiling area with the length of Taylor instability quite long.

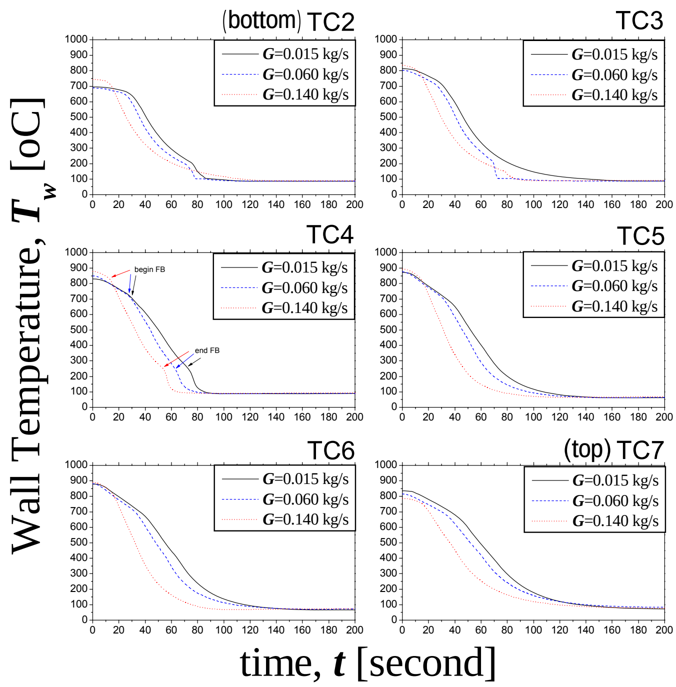

Figure 4. Transient temperature for each TC point with three values of G

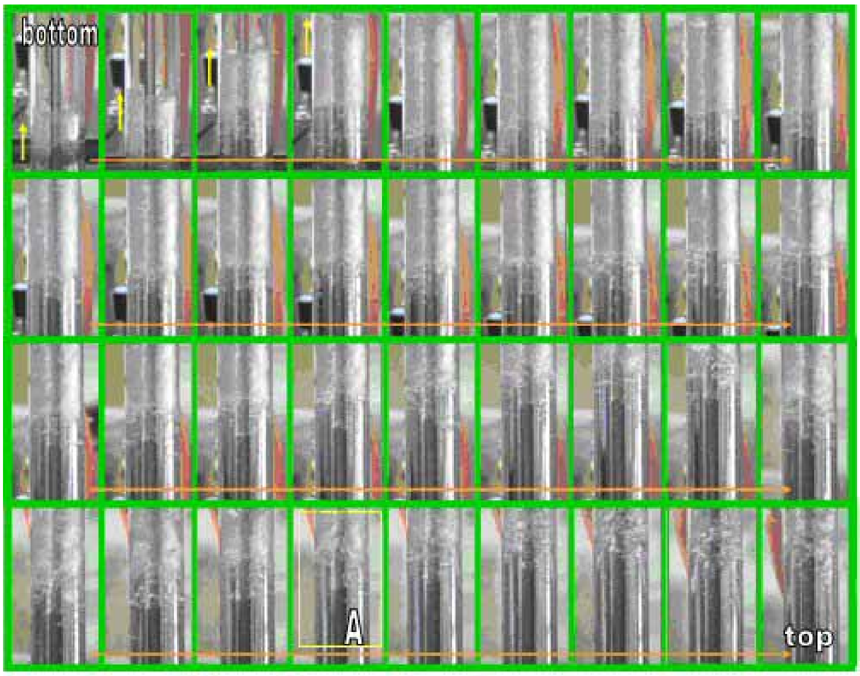

Figure 5. Photos for Boiling Visualization at $T_{initial}$ = 850°C and G = 0.140 kg/s

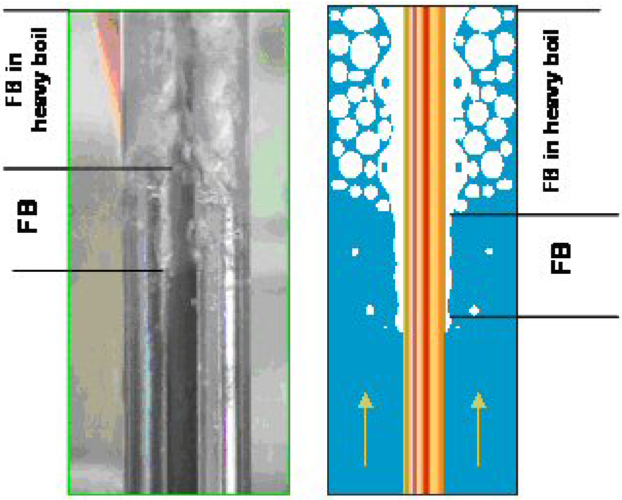

Figure 6. Schematic of boiling regime for high temperature case

Surrounding this area, water is not stable, there are many boiling occurred with number of big bubbles size in water flow (heavy boil). Bubbles growth becomes bigger near upper or water surface. This is obvious, that temperature of heated rod in upper position is still hot, moreover based on observation of Fig. 5 that in heavy boil water there is no contact water to quartz glass of inner surface. It indicated that the quartz surface was still hot (temperature is higher than saturation temperature).

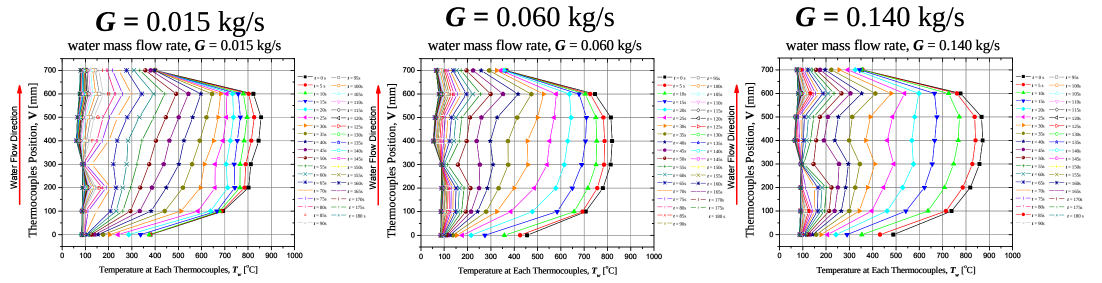

Figure 7. Transient temperature for each position of thermocouples during cooling process from t=0 until t=200 s.

Transient temperature for each position of thermocouples during bottom reflooding process, it shown in Fig. 7.

Fig. 7 shows that, at the beginning temperature profile is similar with sinusoidal curve, then after few minutes it was changes concerning to cooling in each vertical position of thermocouples. Temperature changes at each point is different and it is depending on water mass flow rate and temperature differences at each point become smaller for decreasing of mass flow rate.

3.2. Heat Flux Determination Method

Heat flux at the heated rod surface was evaluated from the temperature history of the measured point by solving the transient heat conduction problem in the inner rod. The following one dimensional heat conduction equation and boundary condition were used:

$$\frac{\partial T}{\partial t} = \alpha\left[\frac{\partial^2 T}{\partial t^2} + \frac{1}{r}\frac{\partial T}{\partial t}\right] \rightarrow \frac{\partial T}{\partial t} = 0 \quad for \quad r = r_{in} \tag{2a}$$

$$\rightarrow \quad T = T_m \quad for \quad r = r_{out} \tag{2b}$$

Where T_m is the measured temperature, α is the thermal diffusivity, r_{in} and r_{out} are inner and outer radii of the heated rod, respectively. The methods of numeric (BTCS finite difference method and tri-diagonal matrix algorithm) were used to solve the differential equation. Time step and mesh size used for the calculation were 1 s and node 0.10 mm respectively.

In Fig. 8, Fig.9, and Fig.10, the operating condition on the experiment moved from right to left and it show typical boiling curve from cooling process in the heated rod during bottom reflooding with 850°C of initial temperature. The curve is obtained from calculating by solving equation (2a) and (2b) using temperature data from thermocouple reading at the point TC4 (300 mm from TC1), to analyze heat flux only one data was used.

At the moment when water was supplied to the test section, the heat flux suddenly jumped up, and then film boiling (FB) took place. Film boiling continued until the minimum stable FB condition was reached, which was followed by a rapid increasing of heat flux due to quenching and subsequent transition boiling (TB). After passing the local maximum heat flux, called CHF, the heat flux decreased gradually in the nucleate boiling (NB) region, and the cooling of the heated rod terminated

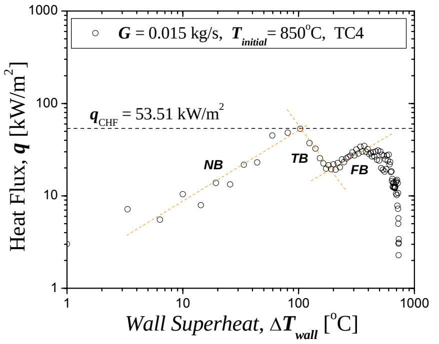

Figure 8. Boiling curve at TC4 for G = 0.015 kg/s

For all mass flow rates, film boiling was occurred, even though there is some strength data pointed out from the beginning of initial temperature decrease. In the mass flow rate G=0.015 kg/s (Fig. 8) from the beginning, the heat flux curve reached the starting point of film boiling in gradually. This is explaining the contribution of heavy boiling due to slower mass flow rate caused by heat transfer to the water in great quantities. The length of film boiling (stable film boiling) in this situation is smaller than other value of mass flow rate (G=0.060 kg/s and G=0.015 kg/s). In Fig.9, for mass flow rate G=0.060 kg/s, the contribution of heavy boiling become smaller than for mass flow rate G=0.014 kg/s and the length of stable film boiling is longer than stable film boiling in Fig.8. Such condition has changes for mass flow rate G=0.015 kg/s (Fig.10), from the beginning, the heat flux curve reached the starting point of film boiling in quickly. In this condition, heat transfer rate from heated rod to the water in mass flow rate G=0.015 kg/s is small enough due to higher mass flow rate and causing the length of stable film boiling become longer than others mass flow rate.

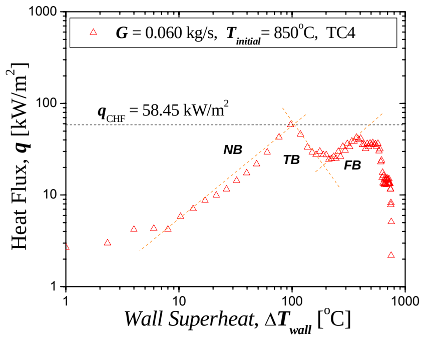

Figure 9. Boiling curve at TC4 for G = 0.060 kg/s

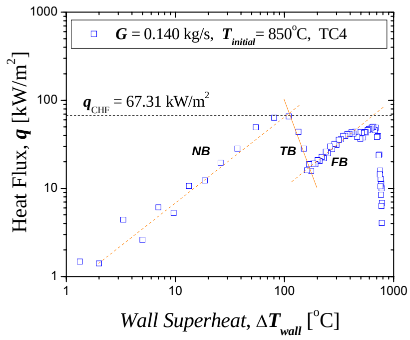

Figure 10. Boiling curve at TC4 for G = 0.140 kg/s

This is obvious, because water flowing has given force to push heavy boil area, and meanwhile rewetting velocity is slower. We can say that the restrictions of boiling heat transfer for all mass flow rate is almost similar caused by the similarity on initial temperature and water temperature. But, the differences of mass flow rate given the differences of stable film boiling length. There are three value of CHF for G = 0.140

kg/s; q_{CHF}=67.31 kW/m^2, G=0.060 kg/s; q_{CHF}=58.45 kW/m^2, and G=0.015 kg/s; q_{CHF}=53.51 kW/m^2.

In comparison to others correlation of CHF, Monde et al. correlation [7] will be use. Monde et al. performed an extensive study of and developed a generalized correlation for CHF in asymmetrically heated vertical parallel plate channels. CHF data was obtained for water, ethanol, R113, and benzene in 10 mm deep rectangular channels formed by a copper heater and an opposing glass plate. Channel lengths of 20, 35, and 50 mm and spacings in the range of 0.45–7.0 mm were investigated, providing channel aspect ratios, L/δ, from 3 to 120.

$$q_{CHF} = \frac{0.16 h_{fg} \times \left[\sigma\left(\rho_f - \rho_g\right)\rho_g^2\right]^{0.25}}{1 + 0.0067 \times \left(\frac{\rho_f}{\rho_g}\right)^{0.6}\left(\frac{L_h}{D_h}\right)} \quad (3)$$

In this experiment, the ratio of channel aspect is 45, in order to 900 mm length and gap size 20 mm. Heat flux of boiling curve also compared with other correlations. Bromley correlation [8] was used for film boiling area. Bromley was conducting a pool boiling experiment with water.

$$h = \frac{2}{3}\left[\frac{\lambda_f^3 \rho_g \left(\rho_f - \rho_g\right) g h_{fg}}{L\left(T_w - T_{sat}\right)\mu_g}\right]^{0.25} \quad (4)$$

where,

$$L_h < 2\pi\left[\frac{\sigma}{g\left(\rho_f - \rho_g\right)}\right]^{0.5} \quad for\ L = L_h$$

$$L_h > 2\pi\left[\frac{\sigma}{g\left(\rho_f - \rho_g\right)}\right]^{0.5} \quad for\ L = 2\pi\left[\frac{\sigma}{g\left(\rho_f - \rho_g\right)}\right]^{0.5}$$

where L [m] is the characteristic length.

The laminar vapor flow (LVP) with Nu = 4-5 for narrow gap was used to ensure that this cases is not vapor-water counter flow situation.

$$q_H = Nu.\left(\frac{k_g}{D_h}\right)\Delta T_s \quad (5)$$

Fig. 11 shows that all boiling curve for three mass flow rate variations including comparison with Monde et al. CHF.

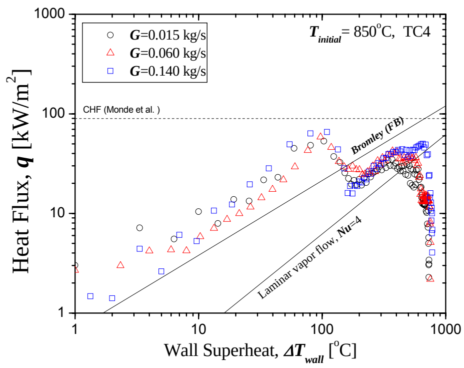

Figure 11. Boiling curve at TC4 for three variations of G

Fig. 11 also shows the differences of CHF based on three variation of water mass flow rate, in this case the values of CHF from experiment is below to the CHF value of Monde et al. This is obvious due to the differences of channel geometry. In the experiment, CHF was increased with the increasing of water mass flow rate, as mentioned above, the contribution of heavy boil has take a part. Following the CHF condition, vapor as an insulating layer over the heating surface is broken and causes decreasing the surface temperature in rapidly way by nucleate boiling into natural convection.

As the similarity of initial temperature of heated rod and water temperature, the area of film boiling is almost occurred at the same position for all mass flow rates. Film boiling curve position is below of Bromley correlation curve, which indicating that this case is not pool boiling condition. Also, film boiling curve has a position in above of vapor laminar flow correlation curve, which indicating that this case is not situation in narrow gap cooling process. The number of vapor is smaller than water during boiling process, even thought vapor blanket was covered the heated rod during film boiling. From this discussion a new correlation concerning heat flux in film boiling area must be define. More study will be conducting to make clearer this problem.

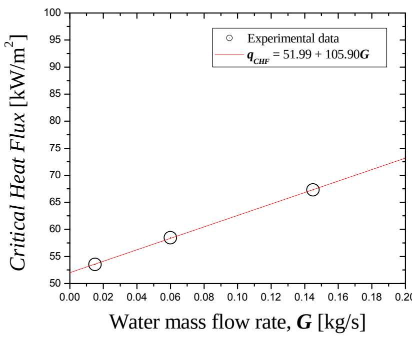

Figure 12. Comparison data between q_{CHF} and G

Fig. 12 shows the comparison of CHF as a function of mass flow rate. The linearity of data from curve of CHF versus G explains a strong connection between mass flow rate changes to CHF value and presenting in linear correlation. This correlation:

$$q_{CHF} = 51.99 + 105.90G \qquad (6)$$

The linearity of CHF correlation as a function of mass flow rate indicating that heat transfer rate was changed in the same wall superheat temperature, between 100°C-106°C due to the similarity of initial temperature.

4. CONCLUSIONS

The experimental study was conducted to investigate a phenomenon of boiling heat transfer surrounding a hot rod simulating fuel cladding using QUEEN-II test section.

The results of experiment show the differences of CHF due to mass flow rate variation. Film boiling area has divided in two categories, quite film boiling and heavy film boiling.

Film boiling region was occurred between pool boiling area by Bromley and laminar vapor flow for narrow gap cases.

CHF in this experiment has a value bellow Monde et al. CHF, indicating the differences of geometry.

The differences of mass flow rate with G between 0.015 – 0.140 kg/s (57%) and CHF between 53.51-67.31 kW/m^2 indicating the effect of mass flow rate increasing to CHF changes only 21%.

5. ACKNOWLEDGMENTS

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6. NOMENCLATURE

G : water mass flow rate [kg/s]
$D_{in-glas}$: glass tube inner diameter [mm]
$d_{out-tube}$: SS304 tube outer diameter [mm]

ρ	: mass density [kg/m^3]
ν_{cold}	: water velocity at cold tube [mm/s]
ν_{rew}	: rewetting velocity [mm/s]
T	: temperature [^{o}C]
ΔT_w	: wall superheat [^{o}C]
r	: inner radius [mm]
q	: heat flux [kW/m^2]
m	: measurement
initial	: initial condition
w	: wall
sub	: sub-cooled
rad	: radiation
CHF	: Critical Heat Flux
f	: fluid (water)
g	: gas (vapor)
g	: gravitation [m/s^2]
L_h	: heated length [m]
D_h	: hydraulics diameter [m]
h	: latent heat vaporization [J/kg]
σ	: surface tension [N/m]
μ	: viscosity [Pas]
λ	: wave length [m]

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