Experimental Study On Rewetting Temperature During Quenching Process In Rectangular Narrow Gap

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Abstract: Thermal management in the event of a severe accident such as the melting nuclear reactor fuel and reactor core (melt core) are need to maintain the integrity of reactor pressure vessel and keep no resulting impact of more substantial to the environment. One way to maintain the integrity of the reactor pressure vessel was cooling of the excess heat generated due to the accident. To get understanding of this aspect, the research focused on determining the rewetting temperature of hot plate cooling on 205ºC, 400ºC, and 600ºC with 0.1, 0.2, and 0.3 liters/sec cooling water flow rate. Experiments were carried out by injecting 85 ºC cooling water temperature into the 1 mm narrow gap at flow rate variations of 0.1- 0.3 liters/sec. Data of transient temperature measurements were recorded using a data acquisition system in order to know the rewetting temperature during the quenching process. This study aims to understand the effect of hot plat initial temperature and flow rate variations on rewetting during rectangular narrow gap quenching process. The results obtain showed that the fastest rewetting occur on cooling water flow rate 0.3 l/s compared with the cooling water flow rate of 0.2 l/s and 0.1 l/s at all rectangular hot plat temperature conditions. Rewetting temperature will increase due to increasing of rectangular hot plat surface temperature. The time required for the occurrence of rewetting will be faster due to higher cooling water flow rate at the same temperature of the rectangular hot plat.
Keywords: rewetting, quenching, narrow gap, nuclear, cooling rate

1. Introduction

Severe accident that occurred at Three Mile Island reactor unit 2 (TMI-2) resulted fuel and core melted (molten core) due to overheated. Molten core accumulated in the bottom of the reactor pressure vessel. The Molten core does not nudging the wall in the reactor pressure vessel because there are cooling water used to cool the molten core, thus forming a narrow gap measuring an average of 1 mm between molten core and reactor pressure vessel inner wall. Cooling water can enter the narrow gap and cooling the surface of molten core. Cooling process that occurs in the narrow gap is that maintaining the integrity of the reactor pressure vessel remains intact. Cooling process that occurs in the narrow gap called quenching, the sudden cooling of a hot surface that occurs when the surface is submerged in the liquid. Water penetration into the narrow gap apart due to gravity will be largely determined by the characteristics of heat transfer in the narrow gap.

The phenomenon that occurred in this case to be a very valuable finding to study the cooling process that occurs in the severe accident and thermal management that will be doing if a similar accident recurring on subsequent reactor operation. By knowing the good thermal management, it is expected to reduce the impact when the accident occur.

Many researches have been done on the cooling process and heat transfer phenomena that occur at TMI-2 accident. The results obtained from that research indicate that there are narrow gap between the melt core and reactor pressure vessel inner wall measuring about 1-2 mm.This gap is formed due to the influence of the cooling water did not touch the molten core withstand pressure vessel inner wall due bouyance force [1-3]. Figure 1 show an illustration of molten core at the bottom of the reactor pressure vessel when severe accident on TMI-2 occur. Severe accident on TMI-2 results 20 tons molten core fall down to the inner wall of reactor pressure vessel bottom.

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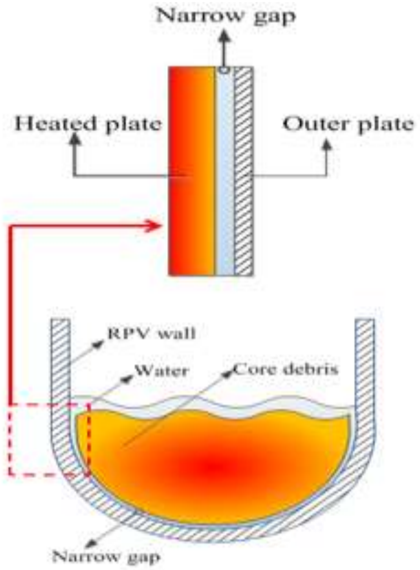

Figure 1. Molten core at the bottom of the reactor pressure vessel

Other researchs results showed that the phenomena of heat transfer in a vertical rectangular narrow gap are many steam covering the heating surface. The steam formed moves upward, while the water flows downward along the wall. The steams prevent contact between the heating surface and the water. Vapor formed on the film boiling regime, ie areas where the heating surface not contact with water. Heat transfer during the cooling of narrow gap is significantly limited by the counter current flow limitation.Heat absorbed in this regime are not significant, and it mean that the critical heat flux will not be achieved and will be very slow. Other factor that influence on the formation of counter current flow limitation is the superficial velocity of fluid cooling and physical properties of the heat surface material. If the cooling water superficial velocity is slower than the vapor superficial velocity, the cooling water will be very difficult to penetrate the vapor resistance. When counter current flow limitationdisapper, the critical heat flux will be easily achieved. Critical heat flux will increase with increasing mass flow velocity. At the the same conditions of temperature and narrow gap size, rewetting on the inner walls will occur more quickly at higher heat flux and critical heat flux. Velocity of a fluid flowing in a narrow gap, the fluid conditions (subcooling), fluid properties, and narrow gap size have significant effect on the characteristics of heat transfer, cooling performance, and transition flow patterns [4-7].

Contact between the fluid with a high-temperature objects continuously was expected in cooling process of an extremely hot surfaces. Generally it can be said that a continuously stable contact called rewetting. Definition of rewetting is re-establishment of fluid contact with the hot surface and cause it to be wet. Very hot surfaces can not be wetted by water when the surface temperature of hot objects is still in film boiling regime. Rewetting process occurs when the surface temperature is below the Leidenfrost point (minimum film boiling). In rewetting process, the heat transfer coefficient has the highest value and the critical heat flux increases with increasing mass flow rate [8]. On rewetting process, the the surface temperature will drop drastically. The effective cooling process on hot surface occurred when the temperature of hot surface under it rewetting temperature [9-12].

From many studies that have been done, there are parameters indicate still not yet observe. One of the parameter is the rewetting phenomena that occurs in narrow gap on the non steady state conditions by varying the initial temperature of the hot plate and the cooling water flow rate. The goal is to know when the rewetting occure in the cooling of rectangular hot plate contained there in narrow gap on the non steady state quenching. This understanding is needed for thermal control management in the event of an accident caused loss of coolant accident (LOCA) and severe accident. The methodology used in this research is to conduct experiments to obtain data on the parameters of the rectangular narrow gap and the initial temperature of cooling water flow rate, determines the rate of decrease in temperature hot plate, discussion of the results obtained and draw conclusions from the results of the analysis.

Agrawal et.al conducted a study on the effects of jet diameter to the rewetting of hot horizontal surface during quenching using Stainless Steel with a thickness of 0.25 mm and initial surface temperature of 800°C. The hot surface cooled by water jet with a temperature of 22°C.The result shows that the rewetting temperature, wetting delay time, and rewetting velocity determines the performance of a cooling hot surface. Figure 2 shows a curve of surface temperature gradients on transient cooling that obtained from Agrawal research [13].

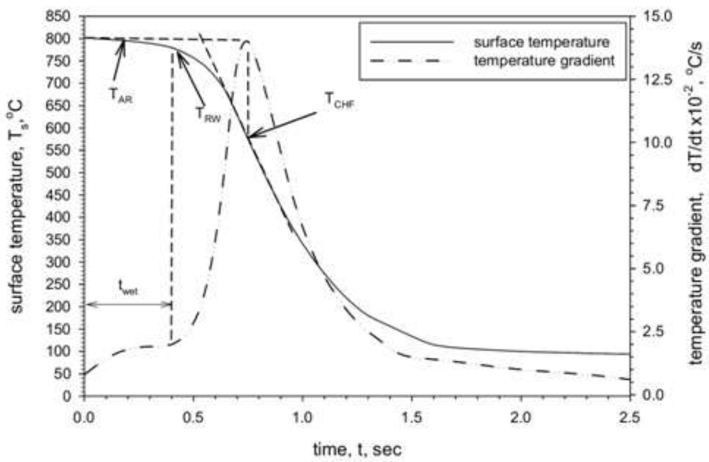

Figure 2. Curve of surface temperature gradient on transient cooling [13].

2. Research Methodology

2.1. Experimental Setup

Experiments were conducted to determine the rewetting phenomena on rectangular narrow gap during the quenching process using open loop system. Figure 3 shows a schematic of the tests performed in this experiment. Open loop system consists of a test piece in the form of two parallel plates 316 Stainless Steel (cover plate and the main plate) so that both of them will form a 1 mm narrow gap. Cover plate heated by heater that connected to the slide voltage regulator with power up to 25 kW. The heat produced by the heater radiation transferred to the cover plate. Heat received by the top cover plate transferred by convection to the bottom of plate. Then the heat is transferred by radiation to the main plate.After main plate reach the desired temperature, thenthe power supply was turned off. Rectangular narrow gap test equipment associated with cooling water loop system. Cooling water loop system circulated water and keep the temperature of the water remains at the desired temperature. Cooling water then flows into the rectangular narrow gap. Inlet water flow through the rectangular narrow gap has 85°C on temperature. The water was forced by a pump into the rectangular narrow gap. Data recorded when electrical power to the rectangular narrow gap test section was turned off. Temperature data during this process recorded using a data acquisition system that connected to a computer. Prior to quenching, infra - red cameras are used to determine the temperature distribution in the heater and cover plate. The temperature data recording will stop after the main plate temperature reaches the same temperature with inlet water temperature.

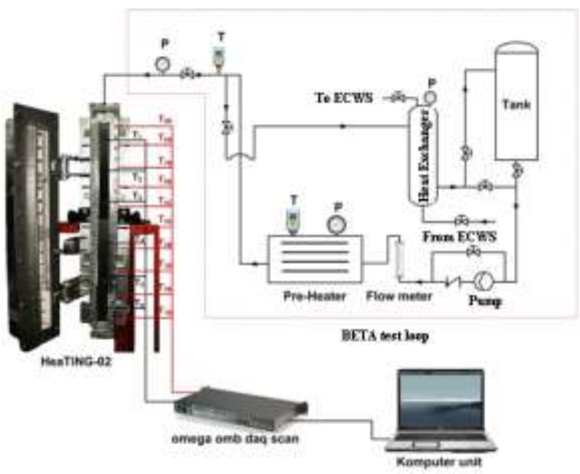

Figure 3. Experimental setup of rectangular narrow gap test section

Thermocouple position using on rectangular narrow gap quenching process on this experiment were depicted in Fig. 4

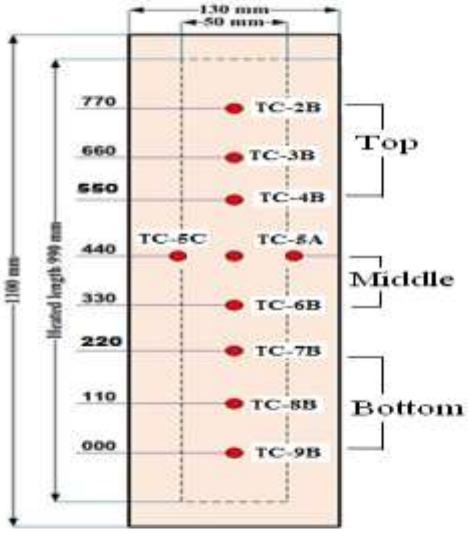

Figure 4. Thermocouple position on rectangular narrow gap experiment

2.2. Experimental Variable

- $T_{initial\ plat}$ = 205ºC, $T_{inlet\ water}$ = 85ºC, narrow gap size = 1 mm, and inlet water flow rate = 0.1 - 032 l/s.
- $T_{initial\ plat}$ = 400ºC, $T_{inlet\ water}$ = 85ºC, narrow gap size = 1 mm, and inlet water flow rate = 0.1 – 0.3 l/s.
- $T_{initial\ plat}$ = 600ºC, $T_{inlet\ water}$ = 85ºC, narrow gap size = 1 mm, and inlet water flow rate = 0.1 – 0.3 l/s.
- Data measurement used in this experiment was the temperature data recorded on the thermocouple 5C only. Temperature data on thermocouple 5C were the highest data and used as heat termination reference that given by heater to rectangular narrow gap when the temperature reading reaches 220ºC, 400ºC and 600ºC. While at the same time, another thermocouple temperature reading indicates below 205ºC, 400ºC and 600ºC.

3. Result and Discussion

3.1. Rewetting Temperature on initial plat temperature 205ºC at varying inlet water flow rate

Rewetting temperature curve at $T_{initial\ plat}$ = 205ºC, inlet water flow rate = 0.1 – 0.3 l/s can be seen on Fig. 5-7.

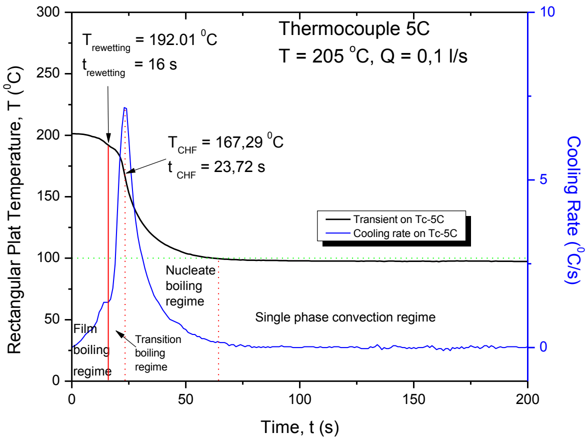

Figure 5. Rewetting Temperature curve at $T_{initial\ plat}$ = 205ºC and inlet water flow rate = 0.1 l/s

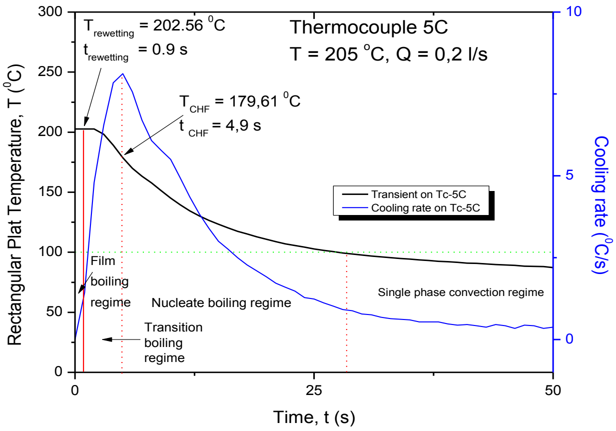

Figure 6. Rewetting temperature curve at $T_{initial\ plat}$ = 205ºC and inlet water flow rate = 0.2 l/s

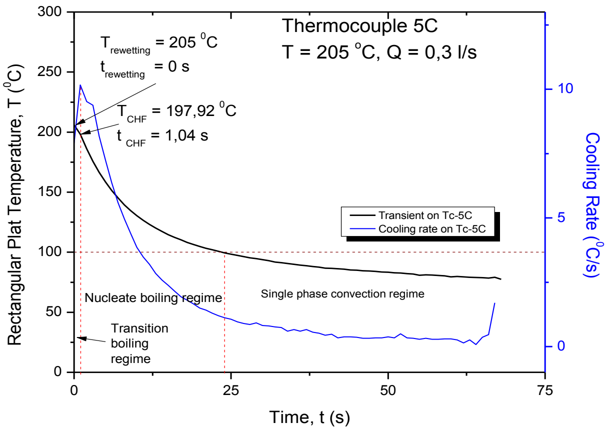

Figure 7. Rewetting temperature curve at $T_{initial\ plat}$ = 205ºC and inlet water flow rate = 0.3 l/s

The experiment results on Fig. 5-7 can be seen on Table 1 with $T_{initial\ plat}$ = 205ºC.

Table 1. Experiment results from Fig. 8-10 with $T_{initial\ plat}$ = 205ºC

$T_{initial\ plat}$ (ºC)	Water flow rate (l/s)	$T_{rewetting}$ (ºC)	$t_{rewetting}$ (s)	T_{CHF} (ºC)	t_{CHF} (s)
205	0.1	192.01	16	167.29	23.72
	0.2	202.56	0.95	179.61	4.9
	0.3	205	0	197.92	1.04

From Table 1, rewetting temperature on rectangular narrow gap had greater value when water flow rate that flowed into the narrow gap increase, as well as the time required or the critical heat flux and rewetting will occur more rapidly than in a smaller flow rate.

The film boiling did not occur on a rectangular plate surface at 205ºC temperature with flow rate 0.3 l/s. Cooling water directly contacted establish when flowed into rectangular narrow gap, which indicated that the temperature conditions were under the minimum film boiling regime (Leidenfrost point). It mean that the heat flux of rectangular heat plat absorbed by the cooling water and the achievement of critical heat flux occurred when the transition boiling regime is exceeded. After the critical heat flux is reached boiling regime change to the nucleat core boiling regime, and finally entered to single phase convection regime.

3.2. Rewetting temperature on initial plat temperature 400ºC at varying inlet water flow rate

Rewetting temperature curve at $T_{initial\ plat}$ = 400ºC, inlet water flow rate = 0.1 – 0.3 l/s can be seen on Fig. 8-10.

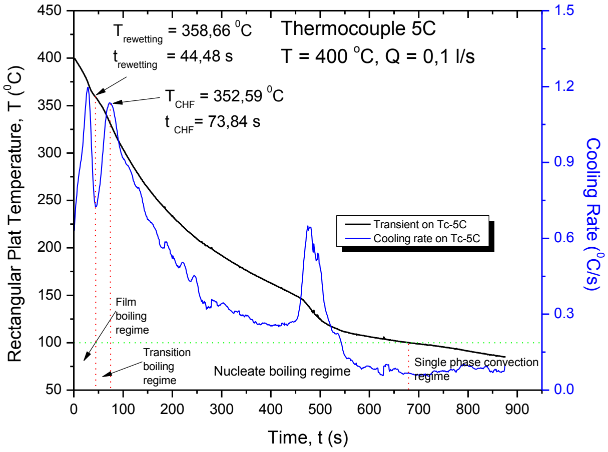

Figure 8. Rewetting temperature curve at $T_{initial\ plat}$ = 400ºC and inlet water flow rate = 0.1 l/s

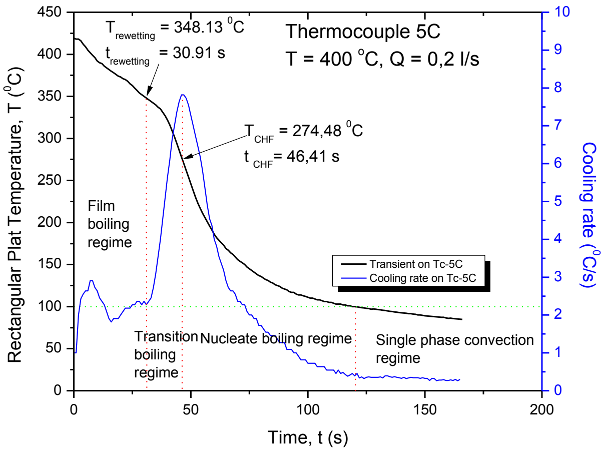

Figure 9. Rewetting temperature curve at $T_{initial\ plat}$ = 400ºC and inlet water flow rate = 0.2 l/s

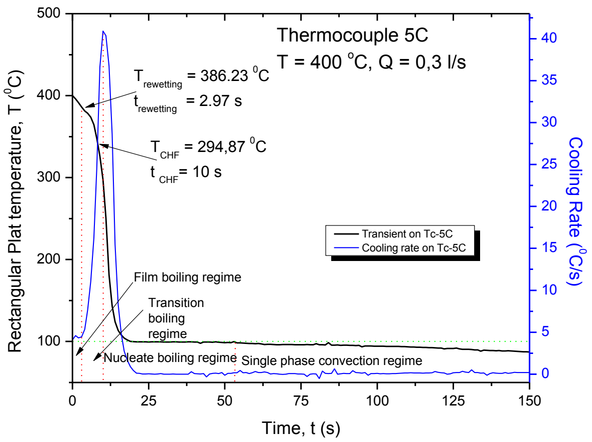

Figure 10. Rewetting temperature curve at $T_{initial\ plat}$ = 400ºC and inlet water flow rate = 0.3 l/s

The experiment results on Fig. 8-10 can be seen on Table 2 with $T_{initial\ plat}$ = 400ºC.

Table 2. Experiment results from Fig. 8-10 with $T_{initial\ plat}$ = 400ºC

$T_{initial\ plat}$ (ºC)	Water flow rate (l/s)	$T_{rewetting}$ (ºC)	$t_{rewetting}$ (s)	T_{CHF} (ºC)	t_{CHF} (s)
400	0.1	358.66	44.48	352.59	73.84
	0.2	348.13	30.91	274.48	46.41
	0.3	386.23	2.97	294.84	10

From Table 2, rewetting temperature on rectangular narrow gap have greater value when water flow rate that flowed into the narrow gap increase, as well as the time required or the critical heat flux and rewetting will occur more rapidly than in a smaller flow rate.

At temperature of 400ºC, all boiling phenomena occured when water flowed into rectangular narrow gap, film boiling regime, transition boiling regime, nucleate boiling regime, and single phase convective boiling. At the film boiling regime, the cooling water can not wet the hot plat. The cooling water will change into steam when it contact with the hot plate on this regime. No great heat absorption occurs in the film boiling, which means that the temperature is not too significant decline when water contact to the hot plat. The condition of film boiling will be dissapear along with the continued contact with cooling water. The loss of the film boiling regime caused the changes to the transition boiling regime. When the Leidenfrost point was reached, cooling water will establish to contact the hot plate surface passing through a narrow gap. This condition is called the rewetting. It is characterized by larger heat absorption of the heat plat by cooling water. On the cooling rate curve looked significant temperature decrease because of heat absorbed by the cooling water. Absorbed heat will reach its peak in the critical heat flux condition. This condition establish continued until nucleate boiling regime and single phase convection regime were achieved.

3. Rewetting temperature on initial plat temperature 600ºC at varying inlet water flow rate

Rewetting temperature curve at $T_{initial\ plat}$ = 600ºC, inlet water flow rate = 0.1 – 0.3 l/s can be seen on Fig. 11-13.

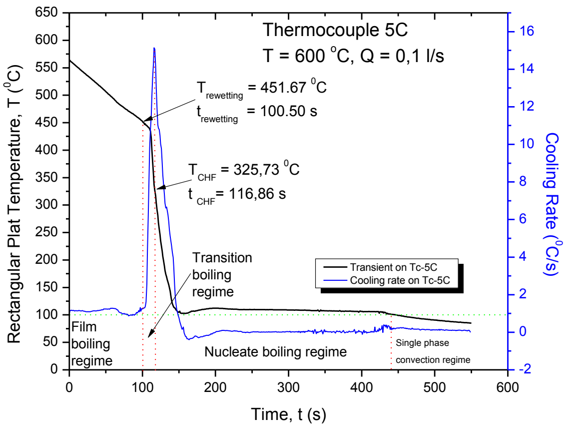

Figure 11. Rewetting temperature curve at $T_{initial\ plat}$ = 600ºC and inlet water flow rate = 0.1 l/s

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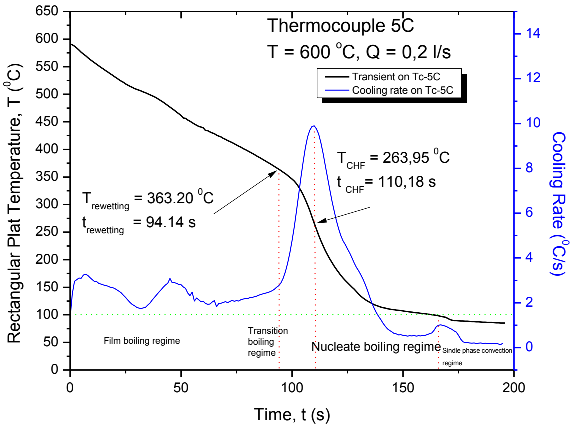

Figure 12. Rewetting temperature curve at $T_{initial\ plat}$ = 600°C and inlet water flow rate = 0.2 l/s

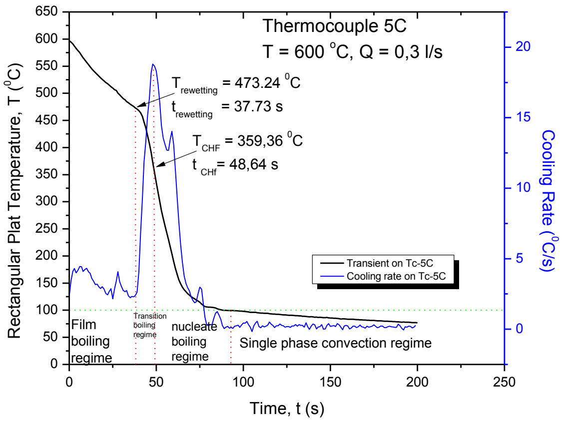

Figure 13. Rewetting temperature curve at $T_{initial\ plat}$ = 600°C and inlet water flow rate = 0.3 l/s

The experiment results on Fig. 11-13 can be seen on Table 3 with $T_{initial\ plat}$ = 600°C.

Table 3. Experiment results from Fig. 11-13 with $T_{initial\ plat}$ = 600°C

$T_{initial\ plat}$ (°C)	Water flow rate (l/s)	$T_{rewetting}$ (°C)	$t_{rewetting}$ (s)	T_{CHF} (°C)	t_{CHF} (s)
600	0.1	451.67	100.50	325.73	116.86
	0.2	363.20	94.14	263.95	110.18
	0.3	473.24	37.73	359.36	48.64

From Table 3, boiling heat transfer on rectangular narrow gap at 600°C temperature have similar phenomena with boiling heat transfer on rectangular narrow gap at 400°C temperature.

Analysis Results from occurrence of rewetting point on rectangular hot plat similar with analysis result obtained by Agrawal et al. The results obtained in this study indicate that the time required for the occurrence of rewetting will be faster due to higher cooling water flow rate at the same temperature of the rectangular hot plat, and rewetting velocity also increases with increasing of water flow rate that flowed into the rectangular narrow gap at a same temperature rectangular hot plate.

Rewetting was characterized by a significant drop in temperature due to the heat absorbed by the water cooling flowed into rectangular hot plat. Knowledgeable temperature, time and rewetting velocity is very important in evaluating the performance of the cooling process of emergency core cooling system when loss of coolant accidents occur. Rewetting was a very important fundamental process on relation to cooling when loss of coolant accident or severe accident occur at a nuclear reactor. This knowledge usefull on thermal management process on nuclear power plant reactor/research reactor accident.

4. Conclusion

Rewetting temperature will increase due to increasing of rectangular hot plat surface temperature. The time required for the occurrence of rewetting will be faster due to higher cooling water flow rate at the same temperature of the rectangular hot plat. Rewetting was a very important fundamental process on relation to cooling when loss of coolant accident or severe accident occur at nuclear reactor. Knowledge of rewetting phenomenon will improve the design of emergency core cooling system on nuclear reactor. This knowledge will very usefull on thermal management process on nuclear power plant/research reactor accident.

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