EXPERIMENTAL STUDY FOR EFFECTS OF BALLOONING AND POWER PEAK ON A COOLABILITY OF FUEL ROD BUNDLE

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ABSTRACT

For a large break loss-of-coolant accident (LB LOCA) in a pressurized water reactor, the clad temperature increases until the reflood phase. This causes ballooned fuel rods and fuel relocation, thereby reducing flow passage area of sub-channel and redistributing the flow and heat transfer in sub-channels. The fuel relocation increase the power at the ballooned region and temperature on the fuel rod. The research on the coolability of the deformed fuel and fuel relocation is very important for a prevention and mitigation of the severe accidents. In the present study, the reflood experiments were performed to investigate the coolability in the ballooned geometry and fuel relocation condition during the LB LOCA for Korean nuclear power plant, APR1400. The coolability experiments were carried out using three kinds of test sections. The first experiments using 6x6 intact rod bundle were performed as a base case. The second experiments simulated the coolability in the deformed fuel using 5x5 ballooned rod bundle. The last experiments were performed using another ballooned 5x5 rod bundle with local power increase to simulate fuel relocation. The fuel relocation phenomena increase the peak cladding temperatures compared with intact and ballooned only rod bundles.

KEYWORDS
Reflood, Ballooning, Fuel relocation, LB LOCA

1. INTRODUCTION

Clad ballooning and resulting partial flow blockage is one of the major concerns associated with the coolability of partially blocked regions in a PWR fuel assembly during a LOCA transient [1]. The characteristics of the clad ballooning and the flow blockage vary according to the LOCA scenarios and the design of the fuel assembly. Several experimental programs had been devoted to perform the coolability after clad ballooning. The major experimental programs include FEBA [2], SEFLEX [3], THETIS [4], ACHILLES [5], CEGB, and FLETCHT-SEASET [6] programs. In addition, several analytical researches had been carried out in association with the experimental programs. Flow blockage models in the COBRA-TF system analysis code were developed and validated based on the FEBA and FLECHT-SEASET test results.

The clad ballooning occurs during a blowdown phase of a large break LOCA [7]. Several in-pile tests such as ANL, and HALDEN tests showed that fuel debris were accumulated in the ballooned region which resulted from fuel fragments dropped from upper regions of the core into the ballooned region. The burst failure of the clad and possible fuel relocation inside the ballooned regions appear around 800 ℃. These fuel relocations were initiated at the time of the cladding burst at the early stage of reflood during a LB LOCA. The fuel relocation causes a local power accumulation and a high thermal coupling between the clad and fuel debris in the ballooned regions. Thus, the fuel relocation might affect the peak cladding temperature, oxidation rate, hydrogen uptake, and quenching behaviors.

Recently, IRSN reviewed the experimental programs for the coolability of partially blocked core performed in the 1980s [8]. The previous experiments did not consider the fuel relocation phenomena and resulting local power increase in the ballooned regions. In addition, the previous experiments did not take into account the high thermal coupling between the clad and the fuel. The estimated maximum blockage ratio was assumed to be about 71%, inferred from NUREG-630 review. Thus, the previous experimental and analytical results are not considered to be conservative. In addition, several past experimental results imply that a flow blockage with high blockage ratio and long blockage length can lead to a significant increase of the clad temperature in the ballooned regions especially under low reflood and low pressure conditions. Therefore, the coolability in partially blocked core with fuel relocation is one of the important thermal-hydraulic safety issues in the revision of current LOCA acceptance criteria. The coolability in partially blocked core in medium and high pressure conditions is one of the unresolved thermal-hydraulic safety issues.

The following phenomena affect the coolability of partially blocked core:

- Flow redistributions between the ballooned regions and the bypass regions (un-ballooned regions)
- Droplet break-up at the entrance of the blockage regions
- Reduction of the coolant velocity and resulting droplet fall-down on the upper surface at the blockage outlet regions
- Single-phase heat transfer enhancement in the blockage regions
- Reflood heat transfers due to the local power increase by fuel relocation

In the present experiments, reflood tests were performed to investigate effects of clad ballooning and fuel relocation on the coolability of partially blocked rod bundle. In order to compare the effects of clad ballooning and fuel relocation, the experiments were performed using three kinds of rod bundles, i.e., intact rod bundle without any ballooned rods, ballooned rod bundle without fuel relocation simulation, and ballooned rod bundle with fuel relocation simulation. These rod bundle are hereafter called intact, ballooned, and fuel relocated rod bundle. The peak cladding temperatures (PCT), rewet temperatures and rewet times are compared for the three rod bundles at the same given conditions.

2. EXPERIMENTAL FACILITIES AND METHOD

2.1. Experimental Facilities

Figure 1 shows a schematic diagram of the reflood test facility, advanced thermal hydraulic evaluation of reflood (ATHER), which consists of a test section, a separating system, a carryover tank for measuring the amount of entrained liquid droplet, a pressure oscillation damping system to control the system pressure, a coolant supply system, and a steam supply system. The test section consists of a heater rod bundle, flow housing, and lower and upper plenums. Trace heaters were installed at the outer surface of the test section to compensate any heat loss to the environment. All components including the test section are well insulated to minimize heat losses to the outside air environment.

Figure 2 shows the cross-sectional diagram of the rod bundles. Each bundle has the same geometrical configuration with the prototype nuclear reactor, APR1400. The heated length, diameter and pitch of the heater rods are 3.81 m, 9.5 mm, and 12.85 mm, respectively. The heater rods are located in a square array and heated indirectly by AC (alternating current) power. The sheath and heating element of the heater rods are made of Inconel 600 and Nichrome, respectively.

The intact bundle (6x6 array) consists of 36 intact heater rods as shown in Figure 2 (a). On the other hand, the ballooned and fuel relocated bundles (5x5 array) consist of 9 deformed heater rods (90% blockage ratio) and 16 intact heater rods as shown in Figure 2(b). The ballooned regions were simulated in a 3x3 rod arrays. The test sections have a rectangular shape with an inner width of 80.2 mm and 68.2 mm for 6x6 and 5x5 rod arrays, respectively.

Ballooning of the clad was simulated by superimposing a pre-shaped Inconel 600 sleeve on the heater rod surface. The maximum blockage length with blockage ratio of 90% extended over 200 mm, with a 100 mm entry taper, and a 50 mm exit taper. The intact heater rods and ballooned heater rods have the same axial power shapes (Figure 4 (a)) while the fuel relocated heaters have different power shape. As shown in Figure 4 (b), the local power at the ballooned region was increased to simulate the local power increase by fuel relocation. All intact and ballooned heater rods have the same total powers. The intact and ballooned rods have the same axial power profiles at the upstream region of the blockage. Thus, the heated length of the fuel relocated heater rods are shorten to 3.302 m in order to have the same total power and to simulate fuel fragments slumping from the upper region of the fuel rod to the ballooned region.

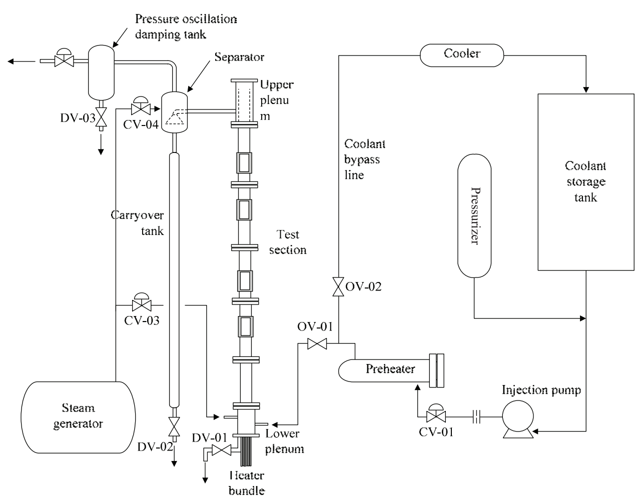
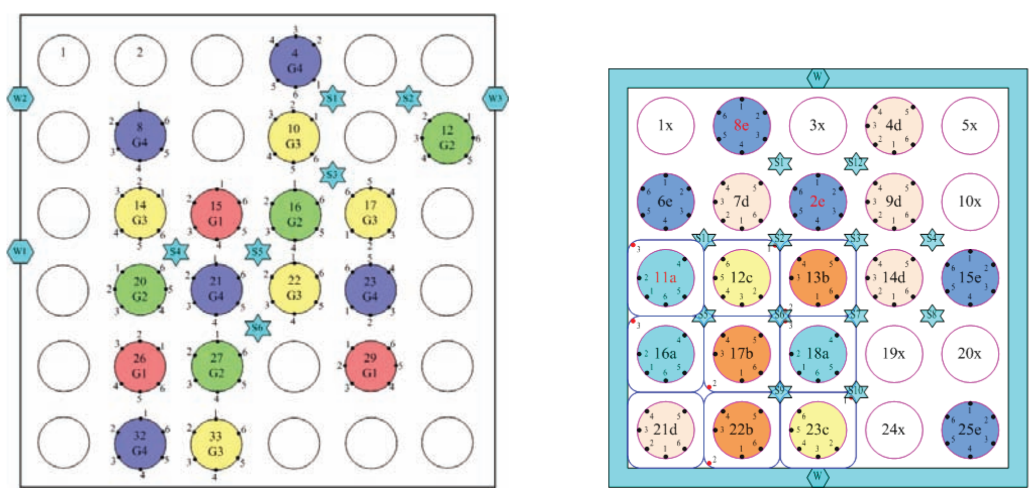


Figure 1. Schematic diagram of ATHER facility



(a) Intact bundle **(b) Ballooned and fuel relocated bundle**

Figure 2. Rod bundle configuration and radial locations of temperature measurement

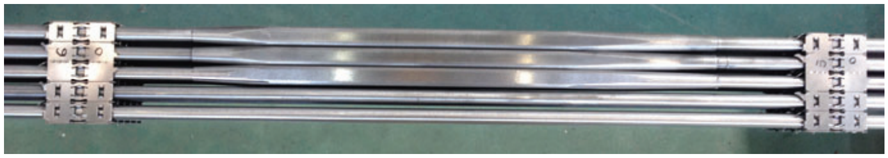
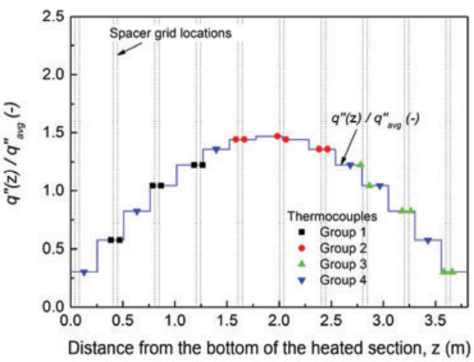
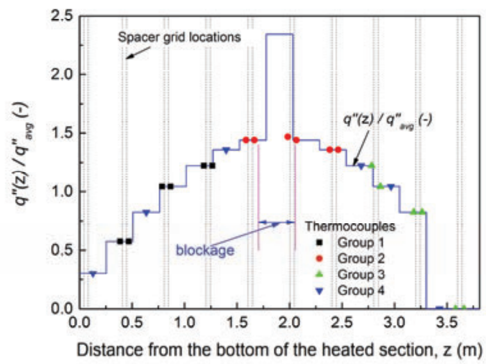


Figure 3. Installed sleeve of 5x5 deformed rod bundle



(a) Intact and ballooned heater rod



(b) Fuel-relocated heater rod

Figure 4. Axial power shape of the heater rods

A total of 11 spacer grids are installed to support the heater rods along the axial location in the test section. The spacer grids with mixing vanes have the same geometry with those used in the APR1400 nuclear power plant. The blockage ratio of the spacer grids used in the present experiment is about 0.48. For instrumented heater rods (colored heater rods on Figure 2), K-type thermocouples with a sheath diameter of 0.5 mm are embedded on the outer surface of the heater rod to measure the heater rod surface temperature. The elevations of thermocouples are marked on Figure 4. A total of 15 K-type thermocouples with a sheath diameter of 1.0 mm are installed in subchannel centers at 11 axial locations along the heated section to measure the steam temperature. Three pairs of K-type thermocouples with a sheath diameter of 1.0 mm were installed to measure the inner and outer surface of the flow housing. Liquid levels were measured using 10 differential pressure transmitters along the test section. The pressures at the inlet and outlet plenums were measured using smart type pressure transducers. The reflood rate was measured using mass flowmeter.

Based on a 95% level of confidence, the uncertainties of the measured data were estimated from the calibration of the measurement sensors and the accuracy of the related equipment [9]. The maximum uncertainties of the measured data for the pressure, steam flow rate, and wall and steam temperatures are estimated to be less than ±1.5%, ±2.5%, ±1.9, and ±2.1 °C, respectively. The maximum uncertainties of the total power and heat flux are estimated to be less than ±2.1% and ±3.7%, respectively. The uncertainties of the Reynolds number of steam and the Nusselt number are less than ±5.4% and ±8.3%.

2.2. Experimental Procedure

The reflood heat transfer experiments were performed according to the following procedure. First, the coolant mass flow rate through the test section was adjusted to the desired value. The coolant temperature at the inlet of the test section were controlled by the preheater at a desired value. After adjusting the coolant mass flow rate and temperature, the coolant flow was diverted from the test section to the bypass line in order to drain the water in the test section. Then, slightly superheated steam enters the test section through the lower plenum and flows upward through the rod bundle, exiting from the upper plenum. The system pressure is measured in the upper plenum. The powers to the heater rods were applied and the maximum heater temperature was brought up to the desired value. The test parameters such as heater rod temperatures, housing temperature, steam temperatures and powers to the heater rods were kept a nearly constant values, and were allowed to stabilize for sufficiently long time to achieve a steady-state condition.

After achieving the steady-state condition, measured data of instrumentations were recorded. The measured data such as the pressure, steam temperature, heater rod surface temperature, steam flow rate, and the total power to the heater bundle were recorded, processed and stored in a data acquisition and control unit. The experiment was initiated by diverting the coolant flow from the bypass line to the test section. The start of reflood was defined as the instant when the collapsed water level is just passing through the bottom of heated section of the rod bundle. After the top end of heated section had been quenched, the experiment was finished.

The test parameters are system pressure, reflood rate, initial maximum temperature, coolant inlet temperature, and the total power of heater rods. Table 1 summarizes the experimental conditions.

Table 1. Summary of experimental condition

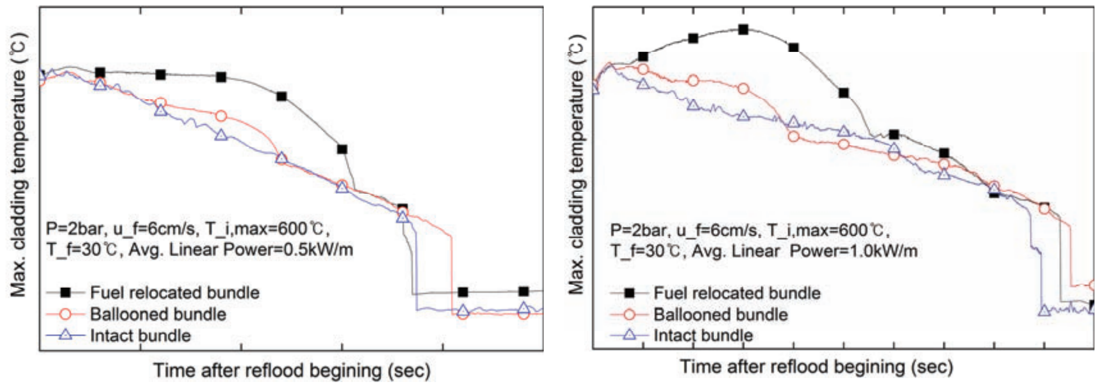
Bundle type	Pressure	Reflood rate	Initial maximum temperature	Coolant fluid temperature	Averaged linear power
Intact / Ballooned / Fuel relocated	2, 4, 6 bar	2, 4, 6 cm/s	600~700 °C	30~80 °C	0.5~1.5 kW/m

3. EXPERIMENTAL RESULTS AND DISCUSSION

Experimental results are plotted on below graphs. Each graph incudes experimental conditions – P is the system pressure, u_f is the reflood rate (coolant fluid velocity), T_i,max is the initial maximum clad temperature, and T_f is the coolant temperature. Figure 5 shows the maximum clad temperatures for the three kinds of rod bundles for the same experimental conditions. For a case of the low power condition (averaged linear power: 0.5 kW/m), there was no significant difference between the intact bundle and ballooned bundle while the fuel relocated bundle had higher maximum clad temperature for the middle of the reflood period. The PCTs were similar, though they showed different behavior of maximum clad temperatures. This means that at low power conditions, there are little effects of ballooning and fuel relocation on the reflood heat transfer, especially the PCTs.

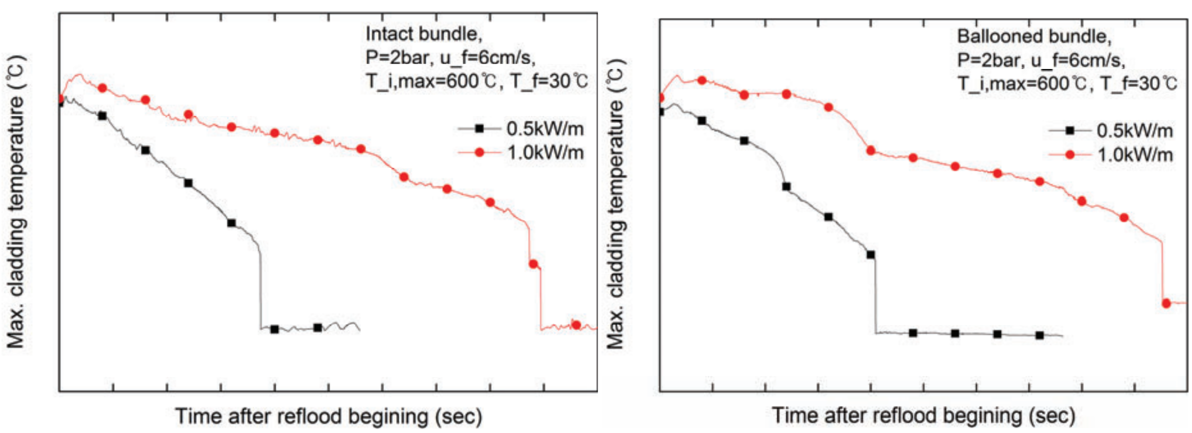
For a case of higher power condition (averaged linear power: 1.0 kW/m), the maximum clad temperature of the intact bundle and ballooned bundle show similar behavior, and the maximum clad temperature of fuel relocated bundle had higher temperature that is similar trend of the lower power case. However, the PCT of fuel relocated bundle was significantly higher than other bundles. This means that the coolability of ballooned rod is similar to the coolability of intact rod, but the fuel relocated bundle has poor coolability for this condition.

The maximum clad temperatures are plotted for different power density on Figure 6. And temperature differences between a PCT and maximum initial temperature are plotted on Figure 7. Here, in Figure 7, the heater rod temperature reached the maximum operable temperature so that the power to the heater rods were terminated to stop the temperature increase. This means that the PCT becomes high at the low reflood rate of 2 cm/s in the fuel relocated bundle. Figure 6 shows that rewetting times of each bundle were longer for high power density. Figure 6 and 7 show that PCT of intact bundle and ballooned bundle is independent on power density while the fuel relocated bundle had power density dependency of PCT.

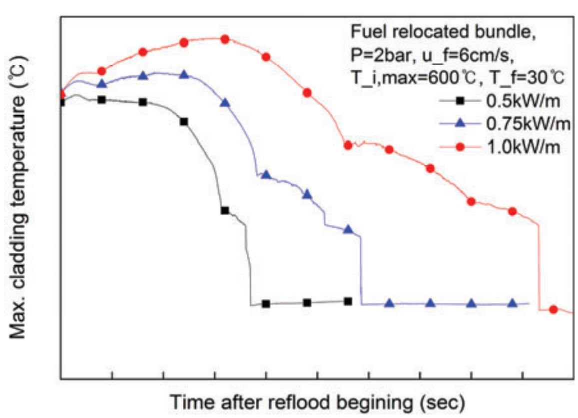


(a) Averaged linear power: 0.5 kW/m (b) Averaged linear power: 1.0 kW/m

Figure 5. Maximum clad temperature behavior for three bundles.

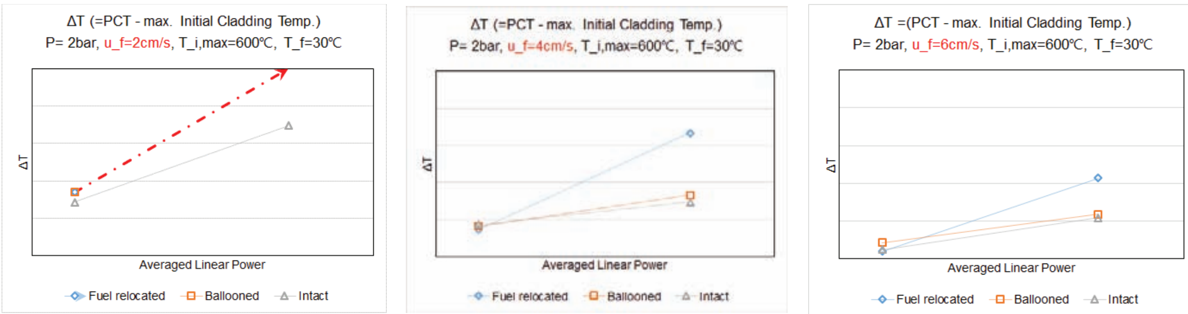


(a) Intact bundle (b) Ballooned bundle



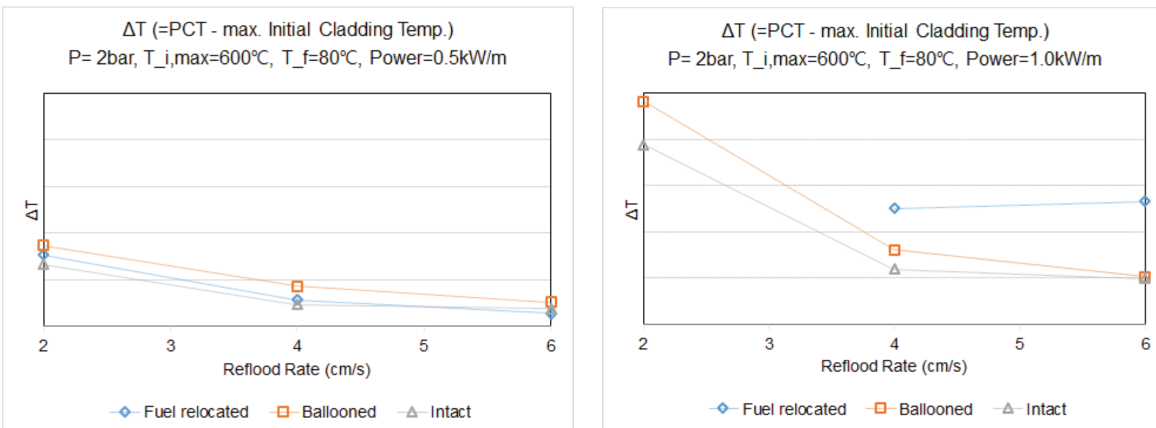
(c) Fuel-relocated bundle

Figure 6. Maximum clad temperature for three bundles.

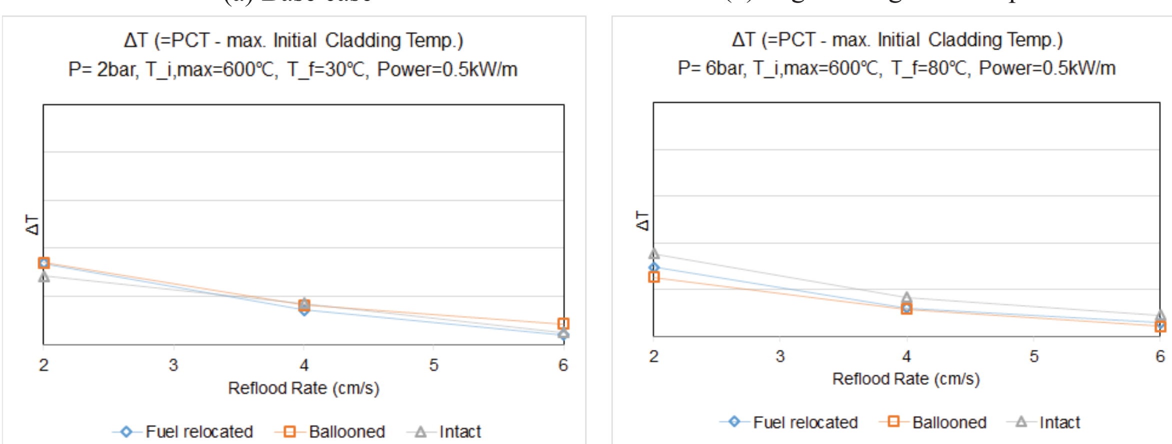


(a) Reflood rate: 2 cm/s (b) Reflood rate: 4 cm/s (c) Reflood rate: 6 cm/s

Figure 7. Geometry effect on the PCT.

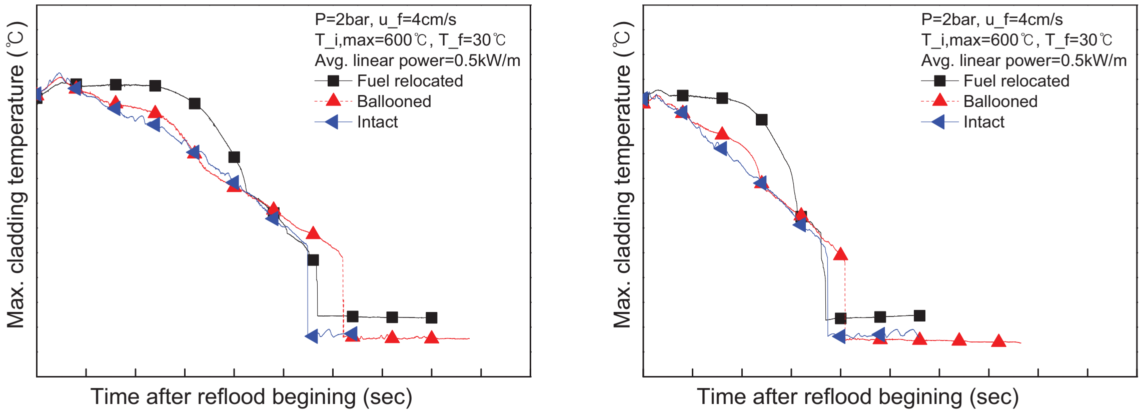


(a) Base case (b) High averaged linear power



(c) Lower coolant temperautre (d) Higher pressure

Figure 8. Reflood rate effect on the PCT.



(a) Reflood rate : 4cm/s (b) Reflood rate : 6cm/s

Figure 9. Maximum clad temperature for three bundles.

The present experiments show that bundles had similar PCT pattern on the reflood rate effect. Figure 8 shows effect of reflood rate. Figure 8(a) is a base case and (b), (c), (d) are different averaged linear power, coolant temperature, pressure, respectively. PCT patterns are similar for each case except the case of the different averaged linear power case (b). For this case, PCTs dramatically increased for 2 cm/s and increase rate of ballooned bundle was higher than intact bundle. This figure concludes that the reflood rate effect becomes major parameter only for higher power density. The experiment using the fuel relocated bundle for 2 cm/s and 1.0 kW/m was skipped because the test facility can be damaged by high temperature. For this reason, there is not the fuel relocated bundle data on the Figure 8(b).

Figure 9 shows reflood rate effect on coolability of bundle. Low reflood rate delayed a cool-down time to rewet the whole bundle. And the cool-down time was independent on the type of bundle.

4. CONCLUSION

An experimental study has been performed to investigate the effects of ballooning and fuel relocation of fuel rod on the reflood heat transfer using rod bundle test facility. Three kinds of heater rod bundles (intact, only ballooned, and fuel relocated heater bundles) were installed to compare the characteristics of reflood phenomena for different rod conditions. All bundles required longer time to cool down the whole bundle for high power density. The behavior of the PCT during reflood tests were different depending on the experimental conditions. PCTs of each bundle dramatically increase for low reflood rate (2 cm/s) and high power density (1.0kW/m) while the PCTs of each bundle were similar for other cases. The ballooned bundle gave similar temperature behavior with intact rod bundle at the same experimental conditions. However, the fuel relocated bundle showed higher PCTs than the other two rod bundles at the same experimental conditions. The higher PCTs in the fuel relocated bundle become more evident as the linear power increases. Thus, the fuel relocation phenomena increase the PCTs, and might result in threatening of a coolability of the reactor core during reflood phase. For the cool-down time, which is required time to rewet the whole bundle, was dependent on the reflood rate and independent on reflood rate.

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