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Experimental study to assess effects of ballooning and fuel relocation on the coolability of fuel rod bundle

Jongrok Kim*, Seok Cho, Jong-Kuk Park, Young-Jung Youn, Sang-Ki Moon

Korea Atomic Energy Research Institute, Daeduk-daero 989-111, Yuseong-Gu, Daejeon 305-353, Republic of Korea

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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 the flow passage area of the subchannels and redistributing the flow and heat transfer in the subchannels. The fuel relocation induces augmentation of power and temperature at the ballooned region simultaneously. In this light, research on the coolability of the deformed fuel and fuel relocation is very important for preventing and mitigating severe accidents. In the present study, reflood experiments were performed to investigate the coolability in the ballooned fuel rod geometry and fuel relocation condition under a LB LOCA for a Korean nuclear power plant, APR1400. The coolability experiments were carried out using three kinds of test sections. The first experiments using a 6 × 6 intact rod bundle were performed as a reference case. The second experiments simulated the deformed fuel using a 5 × 5 ballooned rod bundle. The last experiments were performed using another ballooned 5 × 5 rod bundle with a local power increase to simulate fuel relocation. The reflood phenomena were scrutinized for these three rod bundles. While there were not substantial differences in the peak cladding temperature between the intact and ballooned cases, the fuel relocated bundle showed high peak cladding temperatures.

1. Introduction

Clad ballooning and resulting partial flow blockage are major concerns associated with the coolability of partially blocked regions in a PWR fuel assembly during a LOCA transient (Grandjean, 2007). 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 have been devoted to evaluating the coolability after clad ballooning. The major experimental programs are FEBA (Ihle and Rust, 1984), SEFLEX (Ihle and Rust, 1987), THETIS (Jowitt et al., 1984), ACHILLES (Pearson and Dore, 1991), and FLETCHT-SEASET (Loftus, 1982). FEBA used a 5 × 5 rod bundle with 9 ballooned rods and various blockage shapes. This program concluded that the coolability of the fuel rod bundle up to 90% blockage is not a severe reflood cooling problem even for flooding velocity as low as 2 cm/s (Ihle and Rust, 1984). SEFLEX used a 5 × 5 rod bundle including 9 ballooned rods that have a gap between the heaters and cladding and compared the results and with those of FEBA. A main conclusion was that the heater rod with a gap has a higher safety margin than a gapless heater rod for the coolability under LOCA conditions (Ihle and Rust, 1987). THETIS applied a 7 × 7 rod bundle with a 4 × 4 blockage and it was shown that a long 90% blockage may not be coolable below a 2–3 cm/s reflood rate THETIS (Jowitt et al., 1984). ACHILLES used 69 rods with 16 blocked rods and compared the PCT for various boundary conditions ACHILLES (Pearson and Dore, 1991). FLETCHT-SEASET compared various blockage geometries using a 21-rods bundle and a 163-rods bundle. In this program, blocked bundles showed a lower temperature than unblocked bundles (Loftus, 1982). In addition, several analytical studies have 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.

Clad ballooning occurs during the blowdown phase of a large break LOCA (Grandjean, 2005). Several in-pile tests such as ANL and HALDEN tests showed that fuel debris 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 at around 800 °C. 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

* Corresponding author at: Thermal Hydraulics and Severe Accident Safety Research Division, Korea Atomic Energy Research Institute, Daeduk-daero 989-111, Yuseong-Gu, Daejeon 305-353, Republic of Korea.

E-mail addresses: jongrok@kaeri.re.kr (J. Kim), scho@kaeri.re.kr (S. Cho), jkpark2@kaeri.re.kr (J.-K. Park), yjyoun1@kaeri.re.kr (Y.-J. Youn), skmoon@kaeri.re.kr (S.-K. Moon).

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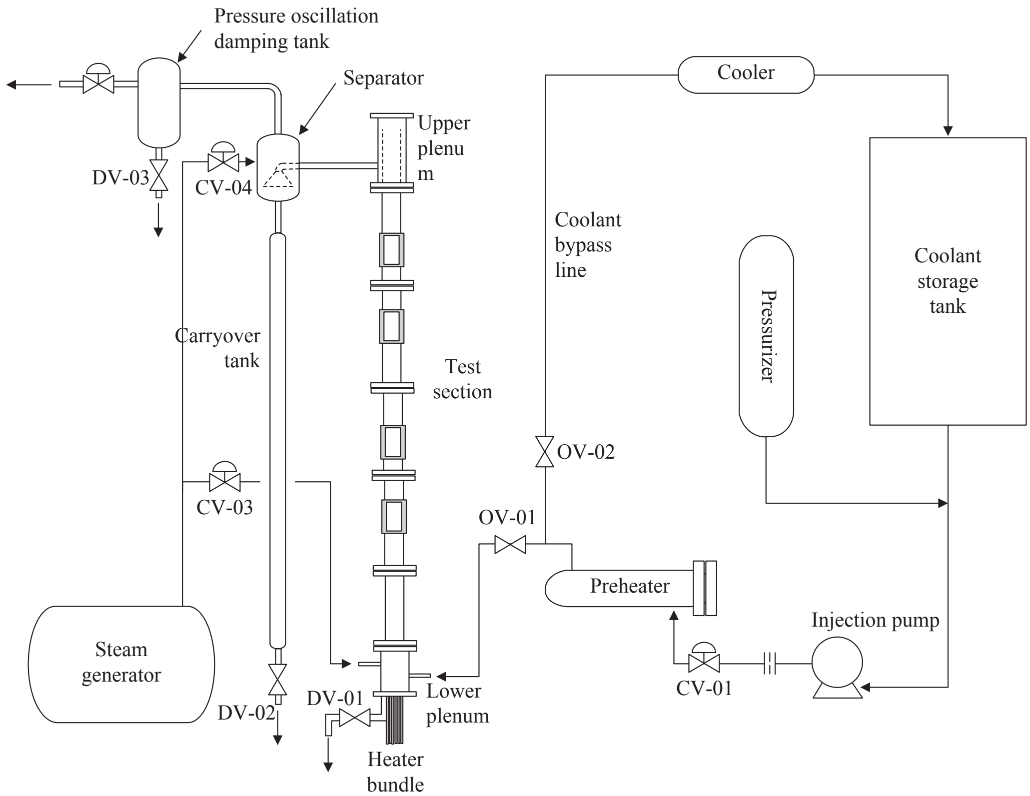

Fig. 1. Schematic diagram of ATHER facility.

causes a local power accumulation and high thermal coupling between the cladding 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 performed in the 1980s for the coolability of a partially blocked core (Grandjean, 2008). The previous experiments show that the cooling ability in a partially blocked condition is acceptable regarding LOCA acceptance criteria. However, these 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 cladding and the fuel. The estimated maximum blockage ratio was assumed to be about 71%, inferred from the NUREG-630 review. Thus, the previous experimental and analytical results are not considered to be conservative. Therefore, the coolability in a partially blocked core with fuel relocation is one of the important thermal–hydraulic safety issues in the revision of current LOCA acceptance criteria.

The following phenomena affect the coolability of a partially blocked core:

- Flow redistributions between the ballooned regions and the bypass regions (non-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
- Change of the heat transfer area between cladding and fluid. There is an increase of the exchange heat transfer area while the cladding deformation increases, which is favourable, but after contact between neighbouring rods, the exchange surface tends to decrease which is penalizing.

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

2. Experimental test facility

2.1. Test section and instrumentation

Fig. 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, two carryover tanks 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, a flow housing, a lower plenum and an upper plenum. Trace heaters were installed on the outer surface of the test section to compensate heat losses to the environment. All components including the test section are well insulated to minimize heat losses to the outside air environment.

Fig. 2 shows a 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 the heating element of the