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Effects of fuel relocation on reflood in a partially-blocked rod bundle

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ABSTRACT

Ballooning of the fuel rods has been an important issue, since it can influence the coolability of the rod bundle in a large-break loss-of-coolant accident (LBLOCA). Numerous past studies have investigated the effect of blockage geometry on the heat transfer in a partially blocked rod bundle. However, they did not consider the occurrence of fuel relocation and the corresponding effect on two-phase heat transfer. Some fragmented fuel particles located above the ballooned region may drop into the enlarged volume of the balloon. Accordingly, the fuel relocation brings in a local power increase in the ballooned region. The present study's objective is to investigate the effect of the fuel relocation on the reflood under a LBLOCA condition. Toward this end, experiments were performed in a 5 × 5 partially-blocked rod bundle. Two power profiles were tested: one is a typical cosine shape and the other is the modified shape considering the effect of the fuel relocation. For a typical power shape, the peak temperature in the ballooned rods was lower than that in the intact rods. On the other hand, for the modified power shape, the peak temperature in the ballooned rods was higher than that in the intact rods. Numerical simulations were also performed using the MARS code. The tendencies of the peak clad temperatures were well predicted.

1. Introduction

As a result of a large-break loss-of-coolant accident (LBLOCA), a rise in the internal pressure in the fuel rod pins due to overheating may cause a permanent deformation of the clad. The deformation of the clad is not uniform due to the local power variation, coolant flow pattern, and manufacturing tolerance. The non-uniform deformation of the clad leads to a partial blocked flow passage in the rod bundle.

The effect of the ballooned shape of the fuel rods has been an important issue, since the coolability of the rod bundle in a LBLOCA scenario is affected by the flow redistribution, droplet impact, and intensified turbulence due to the blockage. Numerous experimental programs were carried out to investigate the coolability of the partially-blocked rod bundle (Cooper et al., 1984; Dore and Pearson, 1991; Hochreiter, 1985; Ihle and Rust, 1984, 1986, 1987). The effects of blockage ratio, blockage length, blockage configurations, and reflood characteristics on the coolability were examined. Grandjean (2006) reviewed the past experimental results. One interesting thing is that for some cases, the maximum cladding temperature in the blocked region is lower than that in the by-pass region. For example, in the FLECHT-SEASET experiments, the maximum temperature just downstream from the upper end of the blockage for the partial-blocked rod bundle was lower than that for the unblocked rod bundle (Hochreiter, 1985; Paik et al., 1985). The beneficial effects resulting from the increase in blockage heat transfer could possibly override the penalty of the flow diversion in the by-pass. The FLECHT-SEASET results were used in the development of improved reflood models in computer codes such as TRAC and COBRA-TF.

Recently, some numerical studies have been performed for the heat transfer in the partially-blocked rod bundle. Ruyer et al. (2013) carried out a CFD study for a dispersed droplet flow downstream from the quench front in a partially-blocked rod bundle. The approach was mechanistic, but the flow regime of interest was limited to a dispersed droplet flow. Ammirabile and Walker (2010) demonstrated the dynamic coupling between the mechanical response of the fuel rods and thermal-hydraulics, and simulated a MT-3 clad ballooning reflood test (Gibson et al., 1982) which is an in-pile experiment on a full-length PWR fuel rod bundle in LOCA conditions.

Although previous works have increased knowledge in the coolability of a partially blocked rod bundle, they did not consider the occurrence of fuel relocation and the corresponding effect on two-phase heat transfer. Some fragmented fuel particles located above the ballooned region may drop into the enlarged volume of the balloon. This phenomenon was first noticed in the 1980s. More recent tests have confirmed the fuel fragmentation and relocation (Billone, 2008; Chomont, 2009; Kekkonen, 2007). Raynaud

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(2012) reviewed past experimental results regarding the fuel fragmentation, relocation, and dispersal. The fuel relocation brings in a local power increase in the ballooned region with corresponding increase in cladding temperature, oxidation, hydrogen uptake, and quenching behavior (Raynaud, 2012). There are very few studies concerning the effect of fuel relocation on the reflood. Hozer et al. (2009) considered both ballooning and fuel relocation in the VVER type rod bundle. However, they did not simulate the whole scenario of a LOCA, and used a uniform axial power profile as a reference case.

The purpose of this study is to investigate the effect of fuel relocation on the reflood phenomena in a partially-blocked rod bundle. Experiments were carried out in a partially-blocked 5 × 5 rod bundle. The clad ballooning is simulated by superimposing a pre-shaped sleeve on a heater rod. Two axial power profiles are tested: one is a typical cosine shape and the other is a modified shape considering the effect of the fuel relocation. The peak wall temperatures in the locally-ballooned rods are compared with those in the intact rods. The experimental results are also compared with the numerical predictions using the MARS code (Jeong et al., 1999).

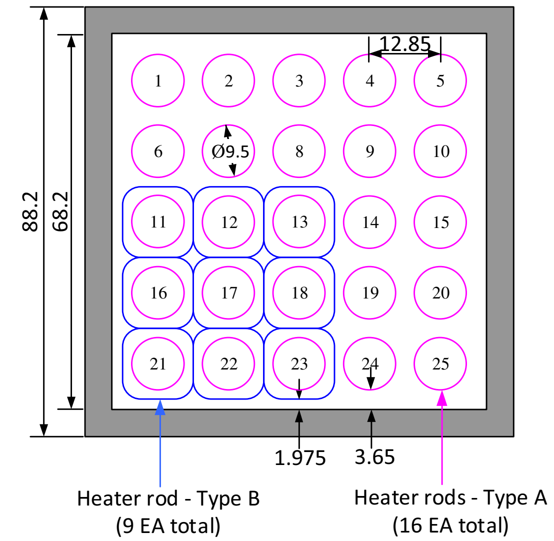

Fig. 2. Cross-sectional view of the partially-blocked rod bundle (unit: mm).

2. Experiments

Fig. 1 shows a schematic diagram of the reflood test facility, which consists of a rod bundle, fluid separator, carryover tank for measuring the liquid mass flow rate, pressure oscillation damper to control the system pressure, coolant supplier, and steam supplier. Fig. 2 depicts the cross-sectional view of the partially-blocked 5 × 5 rod bundle assembly. There are a total of 25 heater rods held by eleven spacer grids. Each heater rod is composed of a sheath layer (Inconel 600), insulating layer (BN + MgO), and heating element (Nichrome wire coiled around a Al_2O_3 cylinder). The outer diameter of the heater rods is 9.5 mm and the heated length is 3.81 m. The type-A rods are intact, and the type-B rods are locally ballooned. Ballooning of a heater rod is simulated by superimposing a pre-shaped sleeve (Inconel 600) onto the rod, as shown in Fig. 3. The sleeve is solid except for a hole for the heater rod. The bottom of the sleeve is 1705 mm above the datum position (heating-start location), and the sleeve is 350 mm long. The maximum blocked region is 200 mm long, and the flow blockage ratio is 90% there. The bundle is housed in a 10 mm thick stainless steel shroud.

The powers of 25 heater rods are radially uniform. Fig. 4 shows the axial power distribution. The abscissa is the elevation from the datum position, and the ordinate is the normalized power. In the figure, the blue line is a typical cosine shape, the red one is the modified shape considering the effect of the fuel relocation. The

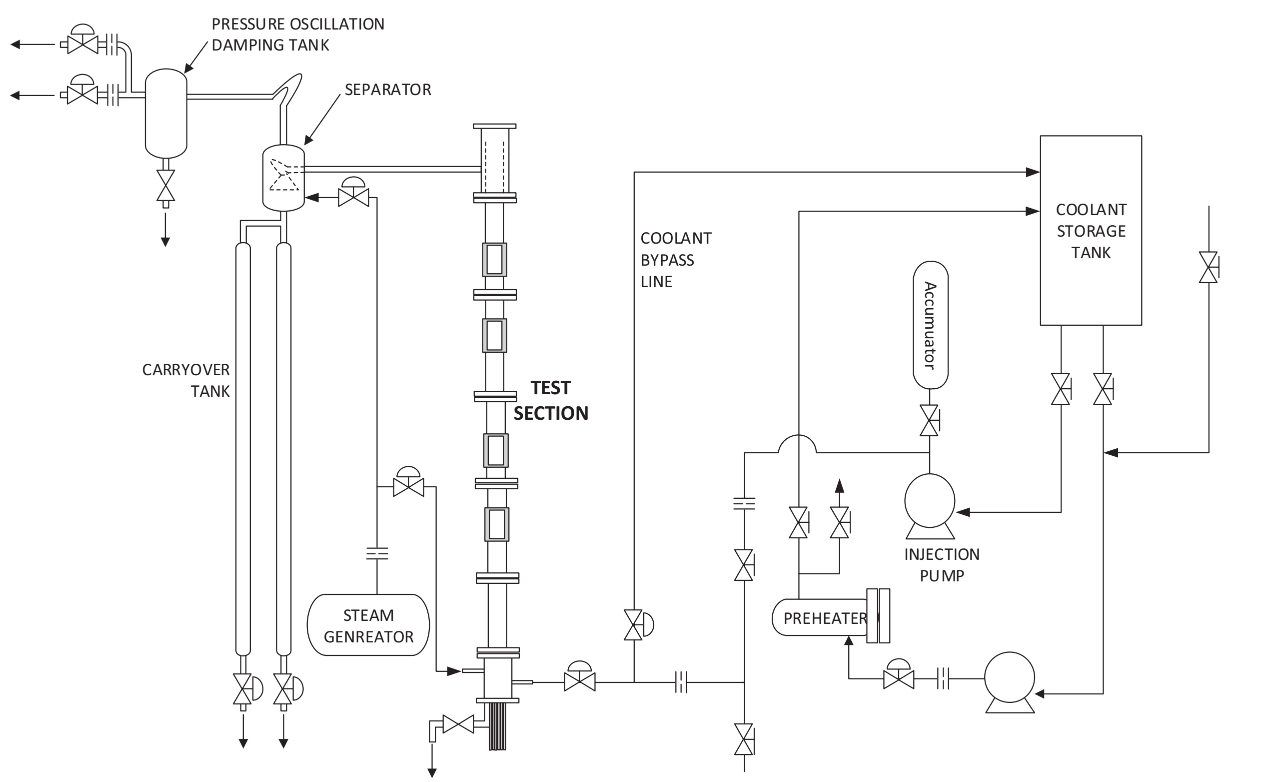

Fig. 1. Schematic diagram of the reflood test facility.

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