Simulation of Dispersal of Fuel Particles with STAR-CCM+

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1. Introduction

Recently, an operational cycle of a power plant has been increasing, and accordingly, a burnup of fuel rod has been also increasing. The increase in a burnup has effects on cladding embrittlement and oxidation and fuel fragmentation and relocation etc. On normal operation and loss of coolant accident (LOCA), relocation of fragmented or pulverized fuel pellets in a deformed cladding mean that distributions of heat sources are changed in a fuel rod and the maximum temperature in a cladding may exceed the limit on peak cladding temperature (1204 ℃). Furthermore, if surface of fuel cladding ruptures due to highly local stresses and fuel fragments disperse through a rupture opening in the cladding, shapes of coolant flow in a reactor core will be changed, which may affect long-term cooling [1]. Because of these effects, the need to revise current acceptance criteria of emergency core cooling systems (ECCS) has been raised, and it is very significant to develop a model that can handle fuel fragmentation, relocation and dispersal (FFRD).

In order to evaluate impacts of dispersed fuel fragments, the location and number of fuel rod ruptures, properties near ruptures in a fuel rod, and sizes of fuel fragments should be basically modeled. In this study, dispersal of fragmented fuel pellets was analyzed in use of information in Studsvik 192 and 198 tests with STAR-CCM+ code. One fuel rod and one burst opening were modeled as a basic step. The results were compared to Studsvik 192 and 198 test.

2. Physical modeling

2.1 Geometry

Geometries for simulating FFRD in CFD code were largely composed of two parts (i.e. a fuel rod and the outside). Regarding a fuel rod, the total length of a fuel rod modeled in CFD code is 174 mm. The reason for reducing the actual length of the effective fuel rod used in Studsvik tests is because the amount of fuel fragments being dispersed out of a fractured fuel rod dominantly may come from traction by gas flow and gravity, which means that fuel fragments that are located relatively far below a burst opening cannot move toward the opening against gravity. The fuel rod in CFD was divided into three areas. The first area was filled with DEM particles, and in consideration of Wire Probe measurement, the second area was simulated into cracked pellets where any particles didn't exist and only fluid could pass through three cracks. The rest area represented plenum, and the height of this area was 103 mm which is the height corresponding to the combined volume of an upper plenum and a pressure line in Studsvik tests. In the CFD simulation, since distension of a fuel cladding couldn't be calculated over time in transient until rupture of the cladding, at least 5% to up to 56% of the cladding outer diameter in 192 model and at least 5% to up to 25% of the diameter in 198 model were applied to each position of each fuel rods to simulate cladding swelling [2,3]. They were only based on radial elongation. The strained claddings in 2 models are shown in Fig. 1 and Fig. 2.

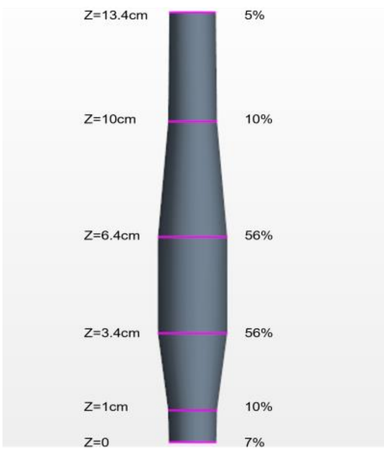

Fig. 1. Strained cladding in 192 model

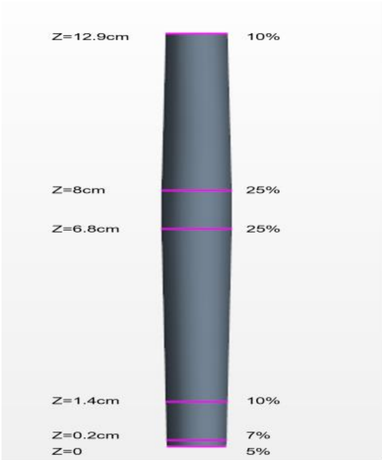

Fig. 2. Strained cladding in 198 model

Each rupture opening in 192 and 198 model was placed within z= 3.4 cm to z= 6.4 cm and within z= 6.8 cm to z= 8 cm where one was an oval shape with a width of 9 mm and a length of 22.7 mm and the other was a diamond with a width of 1.6 mm and a length of 11 mm.

As for the outside of a fuel rod in both 192 and 198 model, there was an enormous cylinder to accept dispersed fuel particles and gas flow, which came from a fuel rod. For example, the entire geometry for simulating 192 model is shown in Fig. 3.

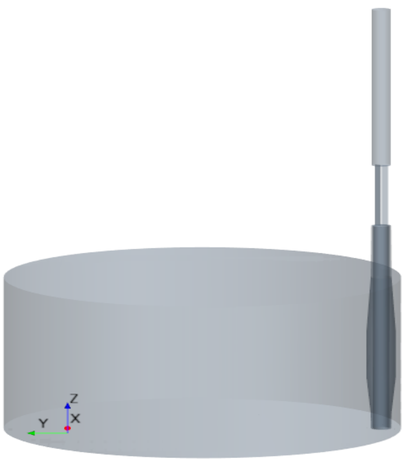

Fig. 3. Entire geometry of 192 model

2.2 Simulation Methodology

DEM model was used to describe fragmented fuel pellets in a fuel rod, and DEM particles were all spherical. In 192 model, the diameter of particles was only 1 mm, but the diameters of particles in 198 model were composed of 1.95 mm and 0.5 mm. Coupled Flow model and Ideal Gas model were used as a flow model because the difference of pressure between the fuel rod and the cylinder was too huge, and K-ε turbulence model calculated turbulence. Schiller-Naumann model was used to calculate drag force, and Two-Way Coupling was used to reflect certainly the interaction between continuous phase and discrete phase. In addition, Studsvik 192 and 198 test analysis in CFD code were performed on the case where the pressure loss coefficient (K) at the rupture opening was 300, and temperature was not considered in this study. Additional initial conditions are shown in Table 1.

Table. 1. Additional initial conditions in 192 and 198 model

	192 model	198 model
Molecular weight of continuous phase [g/mol]	50	
Absolute viscosity [Pa*s]	5.5E-5	
Inner pressure [MPa]	8	
Outer pressure [MPa]	0.1	
Density of particles [g/cm^3]	10.44	
Total mass of particles [g]	94.49	78.76
Total number of particles [#]	172850	2316

The initial conditions were set assuming the situation just before a rupture in a fuel cladding occurred, so it was assumed that all fragments that could move in the rod were completely relocated before starting simulation.

3. Result

The total amount of dispersed particles in 192 model was about 60 g, and about 63 % of the initial mass in the rod was dispersed. In comparison with Studsvik 192 test where the mass loss measured following the LOCA test was 68 g [3], about 8g was less lost. At about 0.086s, the pressure in plenum reached atmospheric pressure. After this point, particles dispersed from the fuel rod were only by gravity without traction of the internal gas. The fuel dispersal and pressure drop calculation are shown on Fig. 4 and Fig. 5. A snapshot for fuel dispersal evolution is shown Fig. 6.

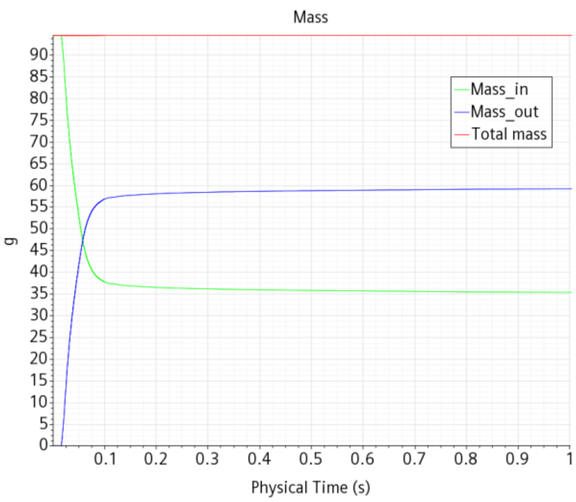

Fig. 4. Dispersed fuel calculation in 192 model.

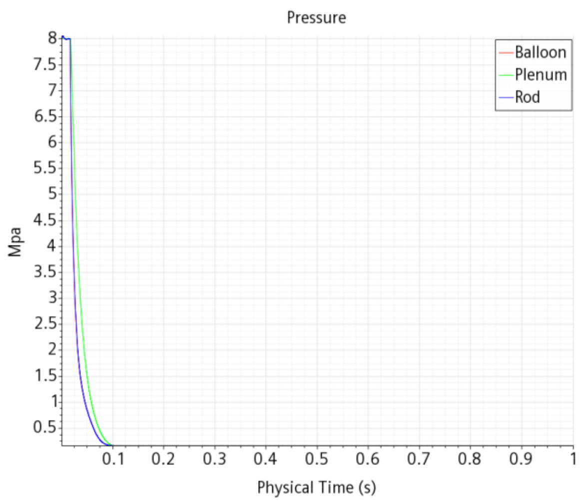

Fig. 5. Pressure drop calculation in 192 model.

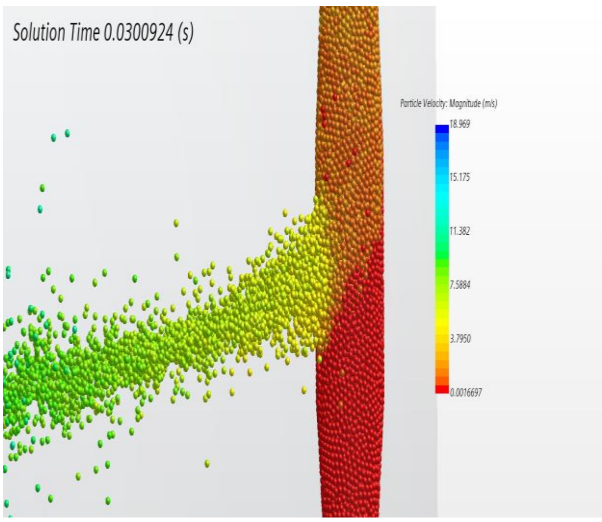

Fig. 6. A snapshot for fuel dispersal evolution.

In 198 model, there were no dispersed particles toward the outside because of DEM particles larger than the maximum width of the burst opening, which was the same as the result of actual experiment. At about 0.7s, a pressure in plenum reached atmospheric pressure. Ultimately, it was confirmed that blockages by the DEM particles near the opening affected fluid flowing out through the opening, so the pressure drop in the plenum in 198 model went slowly than one in 192 model. The pressure drop calculation in 198 model is shown on Fig. 7.

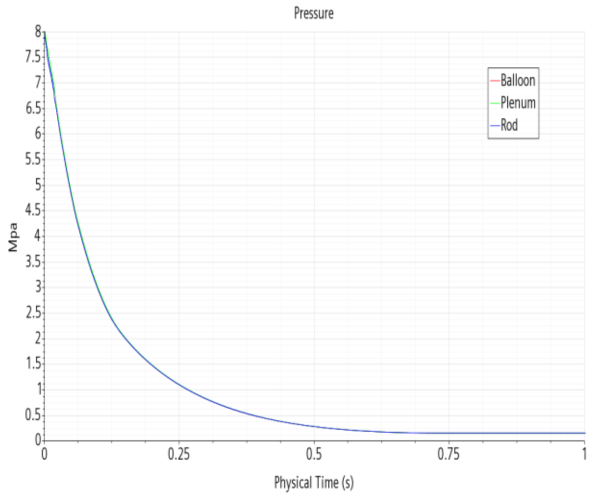

Fig. 7. Pressure drop calculation in 198 model.

4. Conclusion

The dispersals of fragmented fuel particles obtained in Studsvik 192 and 198 tests were analyzed with the DEM model in STAR-CCM+ code. It was found that the amounts of dispersed particles were predicted quite accurately. However, the pressure drops over time were not reasonably simulated mainly due to the limitation of DEM model. To obtain an enhanced result, it is necessary to apply the drag models and mesh control method overcoming the limitation of DEM model.

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