Numerical investigation of debris remelting in RPV lower head by a multiphase particle method

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Abstract: Debris remelting may play an important role in the progression analysis of severe accidents and the safety design of nuclear power plants. This paper developed a multiphase moving particle semi-implicit (MPS) method by coupling the fluid-solid interaction, solid-solid interaction, heat transfer and phase change models. Then, the debris remelting in reactor pressure vessel (RPV) is simulated, and the influence of debris size and decay heat power via local hot spots is investigated.

Keywords: MPS method, Debris remelting, Local hot spots, Fluid-solid interaction, Phase change, Multi-time scale

1. Introduction

In a postulated severe accident of light water reactors, the melt core may drop into the lower plenum of the pressure reactor vessel (RPV) that is full of water. Then, a particulate debris bed may take place, and it would melt again (namely, debris remelting) and form a melt pool after the boil-off of water. Next, the RPV lower plenum might be melted through after or during the melt pool formation. Because the debris remelting may a quite slow process, the formed local hot spots would be a great threat to the integrity of the RPV lower head. The study on debris remelting is of great significance to deepen the understanding of the progression in severe accidents.

This study developed a multiphase moving particle semi-implicit (MPS) method to simulate the debris remelting phenomenon by coupling various advanced techniques in literature. Specifically, the passive moving solid (PMS) model for fluid-solid interaction [1], the discrete element model (DEM) for solid-solid collision in Ref. [2], the heat transfer model, and the solid-liquid phase change model in Ref. [3] are coupled into our inhouse developed MPS method. In this manner, the complicated multiphase flow and heat transfer phenomena during debris remelting can be simulated.

Based on the developed method, the influence of local hot spots in various cases with different debris size and decay heat power are investigated.

2. Numerical methods

The flow and solid motion are calculated as follows. Each solid body is discretized into a set of solid particles. The fluids are discretized into different kinds of fluid particles. Based on the PMS model [1], first, all the solid particles are regarded as fluid particles, which are solved based on the Navier-Stokes equations. Then, the governing equations of the solid body motion are applied the solid particles belonging to a solid body to calculate the translational and rational motion of the solid body. At the same time, the collision forces among solid bodies are considered by DEM with a much small time step when the velocity and position of solid particles are updated.

Heat transfer and the phase change model are computed as follows. Heat transfer is considered for all the particles including the solid particles, the fluid particles, and the RPV wall particles. When solid and wall particles are melted, they will be converted to the corresponding liquid particles. Meanwhile, viscosity is abruptly increased to represent the solidification of the liquid particles.

After some parts of the solid bodies are melted, the relocation flow of the solid-liquid system will take place. However, the relocation flow (in seconds) is much faster than the melting of the solid bodies (in hours). Therefore, a speedup algorithm is developed to simulate the multi-time-scale phenomena in the debris remelting process. Specifically, first, both the relocation flow and heat transfer are simulated for a short time, during which

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the relocation reach an equilibrium state. Second, the flow is neglected and only the heat transfer is calculated implicitly for a long time with a large time step. After a significant amount of debris is melted, the calculation will loop to the first step.

3. Results and discussion

The typical simulated results are presented in Fig. 1 and 2. The upper failure point was observed, which was caused by the heat convection in the top metal layer, as shown by the temperature gradient in Fig. 2. Meanwhile, the lower RPV wall was also seriously ablated. This was mainly caused by the local hot spots near the wall, considering that the solid oxide was not completely melted, as shown in Fig. 1.

From the simulated results, the influence of debris size is as follows. When the debris size was small, the heat transfer was sufficient among solid bodies, and thus the metal solids were melted first. A top melt pool was formed, and the heat convection inside the melt pool caused the upper failure point. When the debris was large, the metal and oxide solids were melted simultaneously. Thus, severe local hot spots took place, resulting in the lower failure point.

Based on the simulated results, the influence of decay power is as follows. When the decay power was lower, heat had enough time to transfer from the oxide solids to the metal solids. Therefore, the metal solids were melted first and formed a top melt pool, which finally caused the upper failure point. However, when the decay power was high, both the metal and oxide solids were melted fast. Even though large local hot spots also took place and caused significant ablation to the bottom wall of RPV, an upper failure point was still observed. This happened because the high decay power could cause the migration of the local hot spots easily, due to the fast melting of the oxide solids.

4. Conclusions

A multiphase MPS method is developed by coupling PMS, DEM, heat transfer model, and phase change model to simulate debris remelting and RPV failure modes. It is found that large debris tended to result in the lower failure point while the small debris tended to cause the upper failure point. The low decay power tended to produce the upper failure point. It is difficult to predict the specific failure point when the decay power was high because the local hot spots could migrate gradually and easily in this situation.

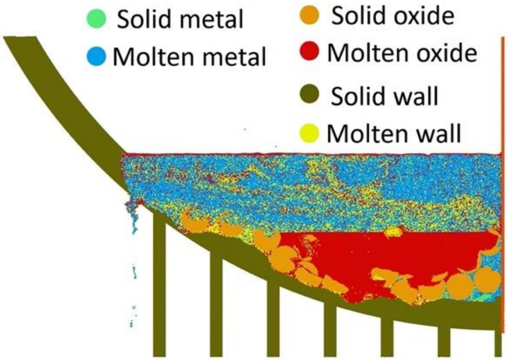

Fig.1 Phase distribution at the RPV failure moment

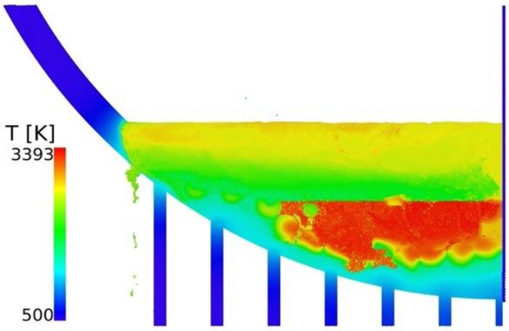

Fig.2 Temperature distribution at the RPV failure moment

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