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# Behavior Analysis of Molten Fuel Discharged Directly into Water without Free-Fall in Air

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## 1. Introduction

Occurrence frequency of a core melt accident in a nuclear power plant is still very low, and decreases continuously due to the application of more additional structure, systems, components and prepared action plans. In spite of that, main phenomena in a severe accident have to be analyzed and assessed in an accident management program for operation license of a nuclear power plant. The accident sequence has to be well predicted, and the accident has to be managed and mitigated based on the analysis results.

A molten fuel-coolant interaction (FCI) is one of the main issues in a severe accident. In-vessel and ex-vessel steam explosions have to be estimated to prove maintaining the integrity of the containment during a severe accident.

The coolant is injected into the reactor cavity for various purposes in severe accident management. One of them is to prevent the breakage of a reactor vessel caused by the thermal or physical load from the molten corium in a lower head of a reactor vessel. In spite of pursuing the strategy for the ex-vessel cooling, the lower head of a reactor vessel can be broken due to the insufficient water level in a reactor cavity. According to the water level, the behavior of molten fuel varies in water.

The purpose of this paper is to analyze the behavior of molten fuel discharged directly into water without free-fall in air. One experimental test performed in the TROI (Test for Real cOrium Interaction with water) facility was introduced and analyzed by TEXAS-V code developed by the University of Wisconsin-Madison for the simulation of FCI [1].

## 2. TROI Test for Submerged Vessel Condition

The analyzed TROI test was performed to investigate the effect of submerged reactor vessel condition [2]. The molten corium at a 70:30 weight percent composition of $UO_2$ and $ZrO_2$ was heated and discharged directly to water. There was no free-fall of the molten corium in air before contacting with water in a test section. The mass and temperature of the released molten corium were about 13.5 kg and 3000 K respectively. The diameter of the nozzle where the molten corium was released was 50 mm.

In the test section, the cross sectional area and depth of water pool were 0.283 $m^2$ and 1.0 m. The initial pressure and temperature of water were 0.15 MPa and 300 K.

The corium fell from the end of the release nozzle by gravity in 0.1 s. At 0.56 s, an external triggering device installed on the bottom of the test section was operated, and the generated pressure wave rose upwards.

The detailed results of the TROI test are explained with those of the TEXAS-V simulations.

## 3. Results of Premixing Phase

There two modes of calculation in the TEXAS-V code. First, the premixing of corium and water is modeled and simulated. The second mode simulates the triggering, propagation and expansion phases of a steam explosion.

In the simulations using the TEXAS-V code for the test, the jet breakup model and fragmentations by Kelvin-Helmholtz instability (KHI) and boundary layer stripping (BLS) were adopted as uncertainty variables for sensitivity analysis. Table I shows the simulation cases and descriptions.

Table I: Simulation Cases

| Name of simulation case | Jet breakup model | Applied fragmentation instability | Coefficient for KHI |
|---|---|---|---|
| T-C1 | Trailing edge | RTI | - |
| L-C1 | Leading edge | RTI | - |
| L-C2-0.02 | Leading edge | RTI, KHI, BLS | 0.02 |
| L-C2-0.01 | Leading edge | RTI, KHI, BLS | 0.01 |
| L-C2-0.005 | Leading edge | RTI, KHI, BLS | 0.005 |

### *3.1 Velocity of Melt Jet*

In the TROI test, the melt jet reached at the water level in 0.1 s after the valve open. At 0.41 s, the temperature detected by the thermocouple installed at 0.4 m of height sharply increased. It means the melt fell through the water with 1.9 m/s of the average velocity. In the visualization test performed before this TROI test, it was shown that the melt jet stream fell to the bottom as a large lump [3].

Fig. 1 shows the velocity variations of the corium jet front in the simulation cases. The initial velocity at the release nozzle was set to 1.0 m/s. The corium melt jet fell downward and the velocity increased due to the gravity acceleration in water. The average velocity of the melt jet was 1.94 m/s.

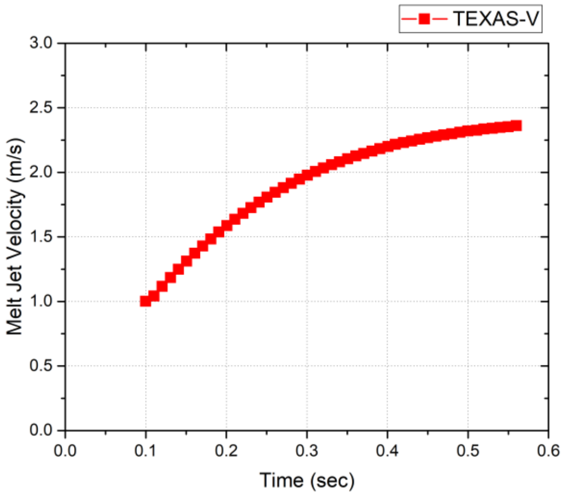

Fig. 1. Melt jet velocity in TEXAS-V simulation

In case of the tests in which the melt jet was released with 1 m of free-fall in air above the water, the melt jet was accelerated by the gravity and the velocity of the melt jet entering water was in the range of 4 to 5 m/s. The velocity sharply decreased due to the resistance on the melt jet front. The breakup of the melt jet occurred in 1 m of water. Otherwise, in this test, the small inertial force of the melt jet does not cause the sharp decrease of the velocity in water. In all the simulated cases, the melt jet breakup did not occur as it was shown in the test.

### *3.2 Corium Particle Size Distributions*

Each simulation case was terminated at 0.56 s, and the premixing simulation results were analyzed. The whole mass of the corium was that of the melt jet in the T-C1 and L-C1 cases. It means the long-wavelength jet breakup did not occur and the melt jet was not fragmented at all. That is because the independent leading corium particles were not assumed in the initial melt discharge condition and generated from the melt jet fragmentation.

Otherwise, when the fragmentation by KHI is considered, the fragmentation on the side of the corium jet was simulated in the simulations. As shown in Table I, the intensity of the fragmentation by KHI was controlled by the coefficient for KHI. In the cases of L-C2-0.02, L-C2-0.01 and L-C2-0.005, the mass portions of the melt jet were 54.1 %, 72.0 %, and 84.0 %. The mass distribution of corium particle size in the simulation cases were shown in Fig. 2. The temperature of some groups of corium particles decreased to the melting point. However, the corium particles were not solidified.

## 4. Results of Explosion Phase

The explosion phases of the cases were simulated based on the results of the premixing phases terminated at 0.56 s. The pressure wave generated from the external triggering device in the test facility was modeled on the bottom of the simulation nodes in the TEXAS-V code.

The impulses of the test and simulation cases were shown in Fig. 3. The impulse generated by the pressure wave from the triggering device was about 3.0 kPa·s. In the cases of T-C1 and L-C1, the impulse of the steam explosion was highly underestimated because the fragmentations on the side and melt jet front were not modeled. Otherwise, when the KHI and BLS were considered in the simulations, the impulse of the steam explosion was overestimated. The impulses of the L-C2 cases were highly varied with the coefficient for KHI. Accordingly, the effect of KHI on the impulse was larger than that of BLS in the simulations. It was found that the KHI coefficient in the range of 0.01 to 0.02 which was used as the conventional or default value of KHI coefficient could overestimate the pressure and impulse of the steam explosion in the condition that the molten corium was discharged into water without free-fall in air.

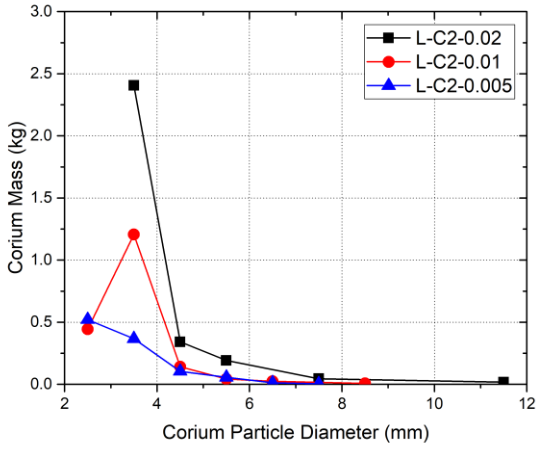

Fig. 2 Mass distribution of corium particle size

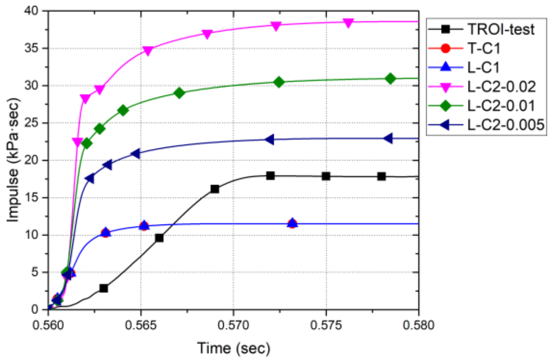

Fig. 3. Impulses of steam explosions

## 5. Conclusions

The behaviors of the molten corium in the test and simulations were analyzed in this paper. In the condition that molten corium discharged directly into water without free-fall in air, the fragmentations by KHI and BLS has to be modeled. That is because the portion of the fragmented mass by KHI was higher than that by RTI with the low velocity of the initial melt jet. The results of the premixing phases varying with the KHI coefficient shows that more small particles are generated with increasing the intensity of the fragmentation by KHI. For the accurate simulation of the fragmentation by KHI, the modeling and coefficients for KHI have to be set properly. The overestimation for the KHI would cause the overestimation of the solidified corium mass in the condition of the deep water in a reactor cavity.

In addition, due to the low pressure difference between the release nozzle and water in the test section, the relatively initial low velocity was set. When this is applied to a plant scale, the low velocity of the corium discharge appears only in case that the pressure difference between the reactor vessel and reactor cavity is very small.

## Acknowledgement

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