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The viscosity effect in corium jet breakup simulation of MATE 06 test

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1. Introduction

If a hypothetic severe ex-vessel accident occurs in a nuclear power plant under wet-cavity strategy, the released molten corium jet from the breached reactor vessel descends toward the concrete bottom floor of the pre-flooded cavity and settles down on it, undergoing vigorous thermo-hydrodynamic fuel-coolant interaction (FCI). In the process of FCI, the molten corium jet experiences complex phenomena such as breakup, quenching, and fragmentation under the multiphase condition caused by the extreme high temperature of the molten corium. The removal of the decay heat generated from the formed molten corium bed on the cavity bottom has been considered one of the most important issues to prevent molten corium concrete interaction (MCCI), which leads to the release of radioactive materials to the environment. It has been well known that the so-formed debris bed coolability depend on particle size, bed porosity, bed shape, jet breakup length, etc [1].

Until now, tremendous research efforts have been put into studying the influential factors mentioned above on the cooability. Among them, intensive works have been contributed to the jet breakup and jet fragmentation. Nevertheless, there have been few studies [2,3] on viscosity effects on jet breakup length. Herein, a numerical study which used a commercial code (STAR-CCM+) and its quantitative results on the sensitivity of viscosity on jet breakup length are briefly presented. In the simulation, MATE 06 test [4] performed at POSTECH has been used as a reference experiment. The numerical work has been carried out under extreme thermal-hydraulic conditions including massive steam generation and air bubbles. Therefore, it may be considered highly meaningful to investigate the viscosity effect under such condition.

2. Establishment of CFD model

2.1 Thermal-hydraulic model

In the present analysis, the simulation model is constructed within the Eulerian multiphase framework, utilizing the detached eddy simulation (DES) turbulence model. The volume of fluid (VOF) method is employed for solving problems encompassing free surfaces and immiscible fluid mixtures. The heat transfer between the liquid and the vaper is applied with a STAR-CCM+ built-in transition boiling model.

2.2 Geometry and mesh

The MATE facility is composed of a rectangular water pool vessel. The dimensions of the water pool's geometry are 0.55 meters in width, 0.55 meters in length, and 2 meters in height as shown Fig. 1. In this model, the nozzle is extended by the free fall distance for the purpose of modeling the process from the moment the molten substance is introduced into the water. An adaptive mesh scheme is effectively employed within the computational domain, as depicted in Figure 1. considering both computational efficiency and accuracy in capturing interface phenomena within two-phase flows.

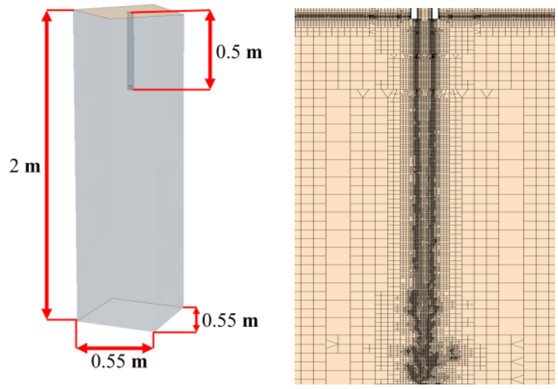

Fig. 1. Geometry and adaptive mesh scheme of 3D jet breakup simulation model.

2.3 Condition of simulation

Table I: Material properties

Properties	Bi-Sn alloy
Composition	Bi 58% + Sn 42%
Density [kg/m3]	8750
Solidus Temperature [℃]	138
Surface Tension (liq) [N/m]	0.4

Table. I presents the material properties of the Bi-Sn alloy as well as the initial condition of the molten corium jet of the MATE test, which is also applied in this study.

Table II : Condition of simulation

	Case 1	Case 2
Jet injection velocity [m/s]	4	4
Jet diameter [mm]	22	22
Coolant temperature [℃]	95	95
Jet temperature [℃]	300	300
Viscosity	Constant	Function of temperature

Table. II outlines the simulation conditions for the two cases. Both are identical to the MATE06 experimental conditions, differing only in their approach to viscosity application. Case 2 considers the variation in viscosity due to the solidification of the molten jet during the cooling process. Guided by the solidification temperature of 138 ℃ noted in Table 1, the melt exhibits liquid alloy viscosity at high temperatures and shifts to solidified alloy viscosity at lower temperatures.

3. Simulation results and discussion

The simulation compares the results for a period of 0.3 seconds for the purpose of the initial behavior of the jet breakup as the viscosity changes. As depicted in Fig. 2, the corium volume fraction is presented for each case, illustrating the jet's distinct behaviors. Notably, the jet's mainstream length measures approximately 1.25 meters in Case 1 and 0.9 meters in Case 2. This difference in length is thought to be due to the fact that in the early behavior of corium, the crust of the leading-edge, solidified by cooling, acted as a resistance to the injection of corium into the water.

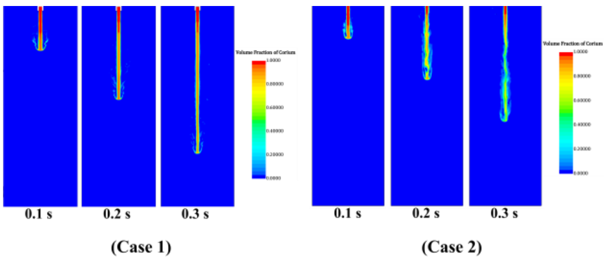

Fig. 2. Result comparison of corium volume fraction

Fig. 3. indicates the steam volume fraction corresponding to each case. In Case 1, as the corium experiences fragmentation and dispersion, the interface between the corium and water expands. Consequently, steam generation occurs in a more extensive and irregular pattern. Conversely, in Case 2, the viscosity changes induced by cooling have somewhat restrained the dispersal of corium, leading to the formation of a crust layer. Consequently, steam generation is observed along the mainstream surface of corium.

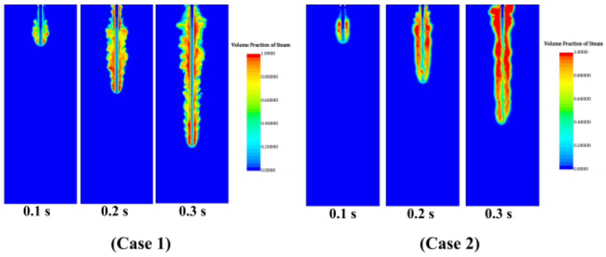

Fig. 3. Result comparison of steam volume fraction

It is evident that in Case 1, the corium undergoes fragmentation and dispersion as it penetrates the water. In contrast, Case 2 reveals a distinct behavior wherein solely the corium initially in contact with water experiences fragmentation and breakup into particles. Subsequently, a markedly reduced number of fragmented particles are observed throughout the injection sequence. Because of the solidification effect, the jet surface layer seems to be more resistant against shear stress. As a result, it is qualitatively observable that the jet penetrates the coolant water less turbulently, generating less fragmentation.

These outcomes can be comprehended by examining Fig. 4. By confirming the viscosity distribution at 0.3 seconds in Case 2, it is observed that a layer of high viscosity has formed along the 3D shape of the corium. This can be attributed to the liquid corium cooling and solidifying, resulting in the formation of a crust along the outer boundary layer of the corium mainstream.

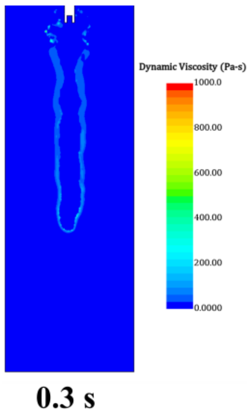

Fig. 4. Viscosity in Case 2 at 0.3 s

4. Conclusion

In this study, the STAR-CCM+ code has been employed to simulate the MATE06 test, and the influence of viscosity on jet breakup has been investigated, taking into account the viscosity effect on the molten corium jet breakup and fragmentation. It has been found that solidification attributed to the viscosity change due to the cooling of the molten material impacts the jet breakup phenomenon. The solidified crust layer formed on the surface of the molten material hinders the smooth penetration of cooling water into the jet, and impedes the active occurrence of fragmentation.

Future study endeavors will yield quantitative results, including parameters such as the mass of fragmented corium and jet breakup length. These quantitative assessments will provide a comprehensive means for evaluating the viscosity effect on jet breakup phenomena.

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