Preliminary Results of Multidimensional Modeling of Fuel-Coolant Interactions with Lagrangian-Eulerian Coupling of Melt and Coolant

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1. Introduction

Fuel-Coolant Interaction (FCI) is a phenomenon in which hot molten fuel interacts with surrounding coolant during a nuclear reactor severe accident and the potential explosive outcome of such an event could threaten the reactor containment integrity. To assess the plant safety against such an energetic event, computational tools have been developed. Examples are: TEXAS - Lagrangian-Eulerian coupling in 1-dimension (Chu, 1989), MC3D - Eulerian modeling of 4-field in 3-dimension (Meignen, 2014), TRACER-II - Eulerian modeling of 4-field (Bang, 2014).

In the international co-work program, SERENA, coordinated by OECD/NEA, whose objectives were code comparison and finding code deficiency, it drew a consensus that modeling jet breakup and coolant void should be advanced. A difficulty in tracing melt distribution more accurately called for Lagrangian treatment of molten fuel and the multi-dimensional aspect of ex-vessel FCI in reactor cavity called for 3-dimensional capability of the code.

In this study, a multi-field, multi-dimensional computational model has been developed to meet the advanced features of FCI code mentioned in the previous paragraph. The molten fuel is modeled in Lagrangian frame and the liquid and gas of coolant fluid are modeled in 3-dimensional Eulerian space. The constitutive relations of jet breakup, interfacial heat and momentum transfer are built.

2. Mathematical Model and Result

2.1 Mathematical Model and Numerical method

The governing equations of continuity, momentum, and energy are given below for Eulerian fluids of gas and liquid. The continuity contains phase change between liquid and gas. The interfacial exchange of momentum and heat are expressed by the exchange coefficients, K_{ji} and R_{ji}. The Lagrangian particles are grouped based on the birth time and the diameter (assumed all spherical). Each particle group exchanges heat and momentum with surrounding fluid of both liquid and gas. The set of governing equations are:

· Fluid continuity equations: *i=g or l, j=l or g*

$$\frac{\partial \alpha_i \rho_i}{\partial t} + \nabla \cdot (\alpha_i \rho_i \vec{u}_i) = \sum_j F_{ji} + S_i \tag{1}$$

· Fluid momentum equations: *i=g or l, j=l or g*

$$\begin{aligned} \frac{\partial}{\partial t}(\alpha_i \rho_i \vec{u}_i) + \nabla \cdot (\alpha_i \rho_i \vec{u}_i \vec{u}_i) &= -\alpha_i \nabla P + \sum_j K_{ji}(\vec{u}_j - \vec{u}_i) \\ &+ \alpha_i \rho_i \vec{g} + \sum_j F_{ji} \vec{u}_j + \nabla \cdot (\alpha_i \underline{\sigma_i}) + S_i \vec{u}_{i,s} + M_{fi} \end{aligned} \tag{2}$$

· Fluid energy equation: *i=g or l, j=l or g*

$$\begin{aligned} \frac{\partial}{\partial t}(\alpha_i \rho_i I_i) + \nabla \cdot (\alpha_i \rho_i I_i \vec{u}_i) &= \sum_j R_{ji}(T_j - T_i) \\ &+ \sum_j h_j F_{ji} + h_{i,s} S_i + \sum_k R_{kfi}(T_{kf} - T_i) \end{aligned} \tag{3}$$

· k-th fuel particle (parcel) momentum equation

$$M_{kf} \frac{du_{kf}}{dt} = -M_{kf}\ g + F_{gkf}(u_g - u_{kf}) + F_{lkf}(u_l - u_{kf}) \tag{4}$$

· k-th fuel particle (parcel) energy equation

$$M_{kf} \frac{dI_{kf}}{dt} = R_{lkf}(T_l - T_{kf}) + R_{gkf}(T_g - T_{kf}) + S_{kf}. \tag{5}$$

In each Eulerian cell, the sum of volume fractions of all three fields is constrained by the unity.

$$\alpha_g + \alpha_l + \alpha_f = 1 \tag{6}$$

The momentum and heat transfer between each phase of fuel particle, coolant liquid and coolant vapor are modeled based on flow regime, which is determined primarily by volume fractions. If the coolant void fraction is smaller than 0.3, bubbly flow is assumed, and the void fraction is greater than 0.7, droplet flow is assumed.

The conservation equations are discretized by the Finite Difference Method and staggered grids are used for Eulerian momentum equations. The convective flux at the control surface is given by the donor cell method. The numerical method uses the implicit multifield technique developed by Harlow and Amsden (1975). Three types of boundary conditions are allowed: inflow, outflow, and constant pressure. It is noted that the open source of K-FIX code (Rivard and Torrey, 1979) was the starting reference for the Eulerian fluid part of the present numerical model.

Molten fuel is a discrete phase in coolant so that Lagrangian treatment of the melt is desired. To model the melt in Lagrangian frame, a cylindrical molten fuel jet is modeled by a series of spherical balls. The breakup of the leading ball is governed by Rayleigh-Taylor instability and (or) boundary layer stripping and the lateral surface breaks up by Kelvin-Helmholtz instability.

2.2 Preliminary Results

The Lagrangian-Eulerian coupled modeling of Fuel-Coolant Interaction has been developed and a set of validation calculations has been carried out. The first calculation was for a 50 mm-diameter sphere falling in air space and the calculated Lagrangian particle trajectory was compared with the analytical free fall equation, as shown in Fig. 1. The result indicates that the numerical treatment of Largrangian particle is well developed.

The second calculation was for the same sphere falling in water and the result was compared with experimental measurement, as shown in Fig. 2. The prediction of the model indicates the sphere falls a little bit eralier that the data, but the overall performance of the model seems satisfactory. The volume fraction of sphere is calculated in each Eulerian cell from its size and location information obtained in Largrangian calculation. Fig. 3 shows volume fraction contour of a single sphere from the injection time to when it reachs the bottom of pool.

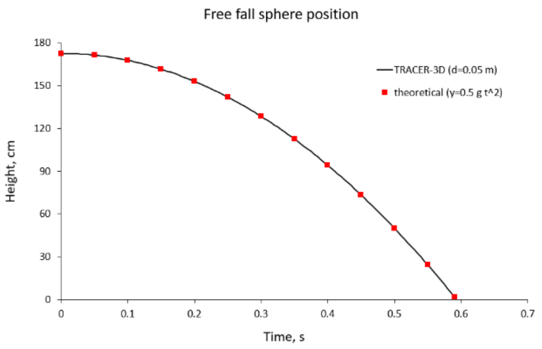

Fig. 1. Simulation of a sphere falling in air.

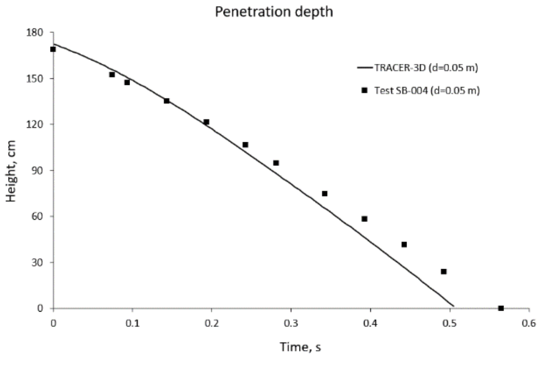

Fig. 2. Simulation of a sphere falling in water and comparison with experimental data.

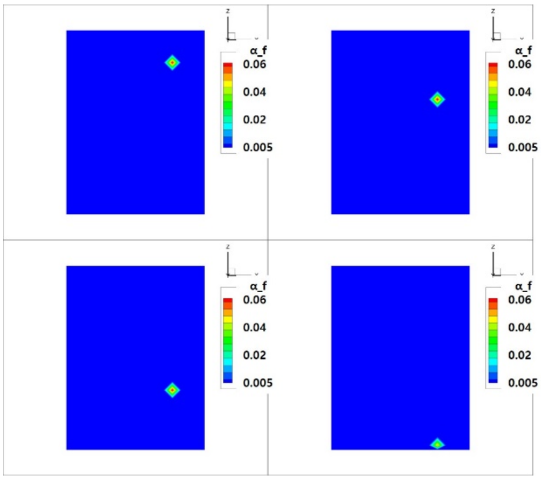

Fig. 3. Volume fracton contour of a sphere falling in water as the case of Fig. 2 (t=0.04, 0.18, 0.35, 0.51s).

3. Conclusion

Multi-field, multi-dimensional computational model for fuel-coolant interactions has been developed. The molten fuel is modeled in Lagrangian frame and the liquid and gas of coolant fluid are modeled in 3-dimensional Eulerian space. The constitutive relations of jet breakup, interfacial heat and momentum transfer are built. The first set of validation calculations indicates the coupling of Lagrangian-Eularian is satistactory. A set of experimental data such as FARO, KROTOS, and TROI will be used for further validation.

Acknowledgments

This work has been financially supported by the Nuclear Safety and Security Commission of Korea.

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