Validation Study of Steam Explosion Code TRACER-II using KROTOS and TROI Tests

Kwang-Hyun Bang *, Hyoung-Tak Kim, Min-Soo Kim
Div. Mechanical Engineering, Korea Maritime and Ocean Univ., Busan, Korea
**Corresponding author:khbang@kmou.ac.kr*

1. Introduction

Since the TMI-2 nuclear accident, prevention and mitigation of severe reactor accidents has been a challenging task in reactor safety study and the recent Fukushima-I accident alerted on expediting installation of advanced measures to secure public safety against radiation hazard. In light water reactors, hydrogen explosion, steam explosion, or molten core concrete interaction could lead to failure of reactor containment.

When molten core contacts with coolant in-vessel or ex-vessel, a violent explosion could occur and the resulting mechanical loading could cause the failure of surrounding structures such as reactor vessel or reactor cavity. To estimate the potential magnitude of steam explosion impulse, many analytical codes have been developed worldwide. Among them, the TRACER-II is a transient, two-dimensional code to calculate mixing and propagation of steam explosion.

Recently, the TRACER-II code has been upgraded extensively to a coupled solver for all four fluids of melt jet, melt drops, coolant liquid, and coolant vapor. Also, length-scale transport equations for melt jet and drops were replaced with area transport equations to better predict the melt drop size. In this paper, a set of validation calculations are reported for the KROTOS and TROI experiments.

2. Mathematical Model

The TRACER-II solves a Eulerian model of multiphase flow which encompasses four fluids of melt jet, melt drop, coolant liquid, and coolant vapor. Phase change between liquid and vapor and melt jet breakup are modeled. The governing equations for j-th fluid are:

- Continuity equation

$$\frac{\partial \alpha_j \rho_j}{\partial t} + \nabla \circ (\alpha_j \rho_j \vec{u_j}) = \sum_i F_{ij} + S_j \quad (1)$$

- Momentum equation

$$\frac{\partial}{\partial t}(\alpha_j \rho_j \vec{u}_j) + \nabla \cdot (\alpha_j \rho_j \vec{u}_j \vec{u}_j) = -\alpha_j \nabla p + \alpha_j \rho_j \vec{g} + \sum_i K_{ij}(\vec{u}_i - \vec{u_j}) + \sum_i F_{ij}\vec{u_i} - \sum_i F_{ji}\vec{u_j} + S_j \vec{u}_j \quad (2)$$

- Energy Equation

$$\frac{\partial}{\partial t}(\alpha_j \rho_j I_j) + \nabla \cdot (\alpha_j \rho_j I_j \vec{u}_j) = \sum_i \dot{Q}_{ij} + \sum_i F_{ij} h_i - \sum_i F_{ji} h_j + h_{j,s} S_j \quad (3)$$

The mass transfer rates between fluids are F_{ij} and the heat transfer rates are $\dot{Q}_{ij}$, which are modeled based on the flow regime and associated constitutive relations. Since this is a Eulerian model, area transport equations are needed to solve for melt jet and melt drop to track the interfacial area. For melt drop,

$$\frac{\partial \alpha_f \rho_f A_f}{\partial t} + \nabla \circ \alpha_f \rho_f \vec{u_f} A_f = \Gamma_{fj} + \Gamma_{fb} - \Gamma_{ff} \quad (4)$$

where the source terms are $\Gamma_{fj} = F_{jb}(\frac{6}{\rho_f d_{jb}})$ for jet breakup, $\Gamma_{fb} = \frac{6\alpha_f C_0}{D_f^2} V_r \sqrt{\rho_c/\rho_f}$ for the secondary breakup of drop, and $\Gamma_{ff} = (\frac{2}{D_f \rho_f}) F_{ff}$ for fine fragmentation. The area transport equation for melt jet is a similar form and more details on the modeling of jet breakup rate F_{jb} is found in the reference [1,2].

3. Result and Discussion

3.1 COLDJET simulation

The validation calculation was first performed for the COLDJET experiment [3] in which molten Woods metal jet of 50 mm in diameter was poured directly into 0.6 m square and 1 m deep water pool in non-boiling thermal conditions. The initial temperatures of jet and water were 85ºC and 40ºC. The jet falling and breakup was clearly visualized. The axisymmetric domain was meshed with Δr=50 mm and Δz=10 mm.

The jet front elevation and the Sauter mean diameter were compared with the experimental data. As shown in Fig. 1, with the reported jet injection velocity of 4.4 m/s which was estimated from visual images at the nozzle tip, the jet falling was a little bit slower than in the experiment. By increasing the initial jet velocity by 20%, the jet front elevation agrees well with the experimental data (red line). The Sauter mean diameter is shown in Fig. 2, which indicates the size of melt drops. At the end of simulation, the Sauter mean diameter was 0.55 mm, which is close to 0.64 mm of posttest debris analysis.

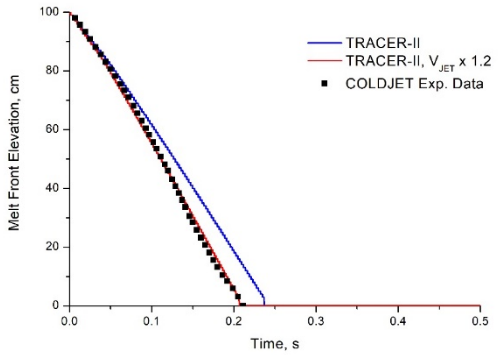

Fig. 1. Jet front elevation in COLDJET simulation

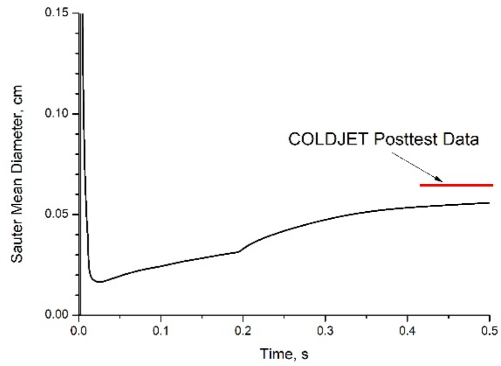

Fig. 2. Sauter mean diameter in COLDJET simulation

3.2 KROTOS and TROI simulations

The past FCI experiments that used real corium melt are limited to a few which include FARO, KROTOS, and TROI experiments. The recent OECD/NEA SERENA project financed the new KROTOS tests conducted by CEA and the TROI tests conducted by KAERI [4]. The validation calculations were performed for one test from each experiment, KROTOS KS-4 and TROI TS-4 tests. The major test conditions are given in Table 1.

Table 1. Test conditions of KS-4 and TS-4

Parameter	KROTOS KS-4	TROI TS-4
Melt comp.	UO_2(80):ZrO_2(20)	UO_2(80):ZrO_2(20)
Melt mass, kg	3.21	14.3
Melt temp., K	2963	3011
Jet dia., cm	3.0 (2.16)*	5.0
Free fall, m	0.5	0.6
Water depth, m	1.1	1.0
Water temp., K	332	333
Pool dia., m	0.2	0.6
Pressure, bar	2.1	2.31
Jet speed, m/s	2.3 (1.6)*	2.8
Trigger time, s	1.04	0.715

*( ): Adjusted input values for simulation

For KS-4 simulation, the initial jet speed was adjusted to 1.6 m/s to match the free-fall trajectory in air space and the jet diameter was also corrected to give the same melt mass.

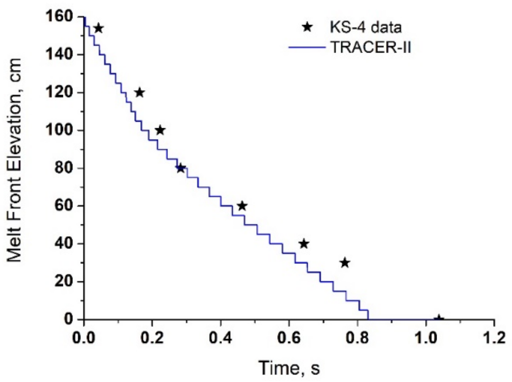

Fig. 3. Jet front elevation in KS-4 simulation

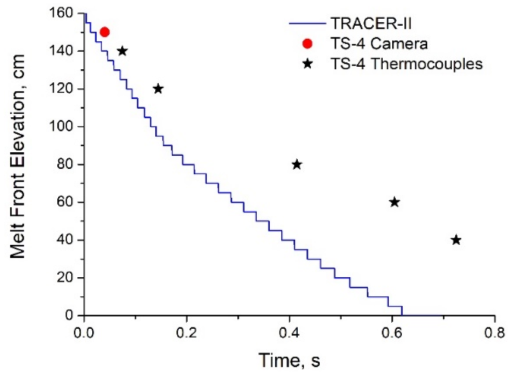

Fig. 4. Jet front elevation in TS-4 simulation

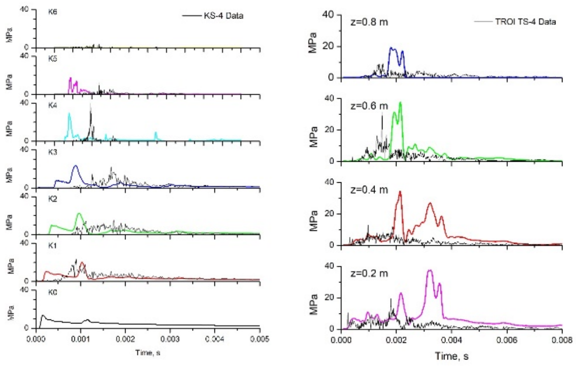

Fig. 5. Comparison of explosion pressure traces

The calculated jet front elevation was reasonable for KS-4 as shown in Fig. 3, but in TS-4 the melt fall was much faster than in the test (Fig. 4). This may be attributed to an uncertainty in jet entrance caused by spray-shape front of initial melt jet in the test. The explosion pressure traces are compared in Fig. 5.

4. Conclusion

The steam explosion analysis code TRACER-II has been extensively upgraded to accommodate a coupled solver for all four fluids. A set of validation calculations were carried out and the results showed that the hydrodynamic capability as well as jet and drop breakup models are good. The explosion pressure traces also showed a reasonable agreement with the test data.

REFERENCES

[1] Bang, K.H., Kumar, R., Kim, H.T., Modeling corium jet breakup in water pool and application to ex-vessel fuel-coolant interaction analyses, Nucl Eng Des 276, p. 153-161, 2014.
[2] Kim, M.S., A numerical study on the jet breakup in melt-coolant interactions, M.S. Thesis, Korea Maritime and Ocean University, 2021.
[3] Bang, K.H., Kim, H.T., Vo, D.T., Experiment and modeling of jet breakup in fuel-coolant interactions, Annals of Nuclear Energy, 118, pp. 336-344, 2018.
[4] OECD/NEA, OECD/SERENA Project Report: Summary and Conclusions, NEA/CSNI/R(2014)15, 2015.