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Validation Calculation of TRACER-3D Code for Corium Experiments

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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[1], MC3D - Eulerian modeling of 4-field in 3-dimension[2], TRACER-II - Eulerian modeling of 4-field in 2-dimension[3]. In this study, to overcome potential shortcoming of these codes, three-dimensional Lagrangian-Eulerian coupled FCI code has been developed (TRACER-3D).

In this paper, validation calculations of TRACER-3D are reported. KROTOS and TROI experiments: recent OECD SERENA experiments using corium, are chosen for validation.

2. Key Mathematical Models

The governing equations of continuity, momentum, and energy are solved for Eulerian fluids of coolant vapor and liquid in coupled with Lagrangian particles of fuel. 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. In each Eulerian cell, the sum of volume fractions of all three fields is constrained by the unity. Detail mathematical description of the code is found in Ref. [4].

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

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 edge is governed by boundary layer stripping and the lateral surface breaks up by Kelvin-Helmholtz instability. As the fuel particle breaks up into smaller particles, the volume of spheres, so called parcel volume, expands. Fig. 1 illustrates the modeling of parcel expansion. The initial expansion speed is provided by Kelvin-Helmholtz instability model.

The expanded parcel occupies many computational cells, as illustrated in Fig. 2. A partial occupation of a cell can be divided into faces, edges, and corners. Current model limits one parcel occupation upto 64 cells.

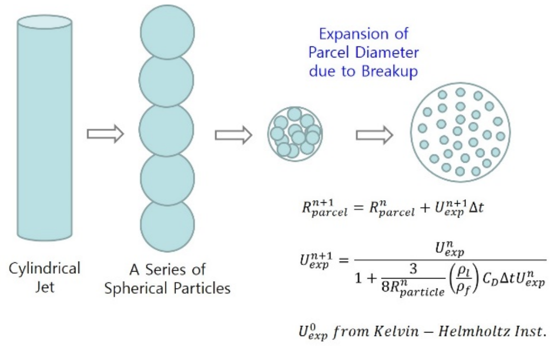

Fig. 1. Jet parcel expansion model

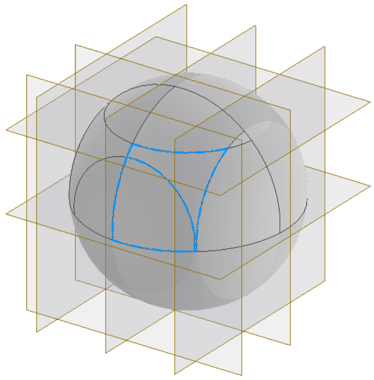

Fig. 2. Volume partition of a fuel parcel over computational cells

3. Code Validation Calculations

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 and TROI tests[5]. 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)*	(2.46)*
Trigger time, s	1.04	0.715

*( ): Adjusted input values for simulation

3.1 KROTOS KS-4

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 during the melt pour time.

Fig. 3 shows the comparison of fuel front location. The fuel falls initially by gravity down to elevation of 110 cm, and it enters water pool, breaks up as it falls through water pool. The comparison of melt front location is excellent despite of very complex and conjugate nature of fuel mixing phenomenon encompassing fuel breakup, evaporation, and multiphase flow regime.

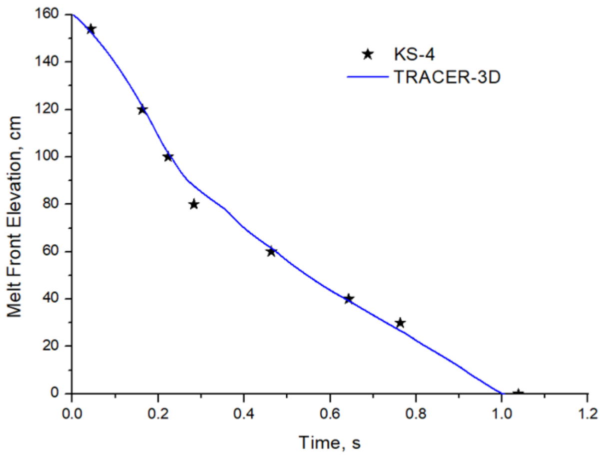

Fig. 3. Jet front elevation in KS-4 simulation

Triggering of explosion was made by applying 15 MPa to the triggering cell at the time of triggering. The void fraction of coolant at the time of triggering is shown in Fig. 4. It is generally low because the coolant is subcooled by 60°C except the near the bottom where it is ~0.6. Such high local void fraction can retard the propagation of explosion. The explosion traces are compared with the experimental data in Fig. 5. The general trend of the explosion propagation is acceptable, although the magnitude of peak pressure is underestimated.

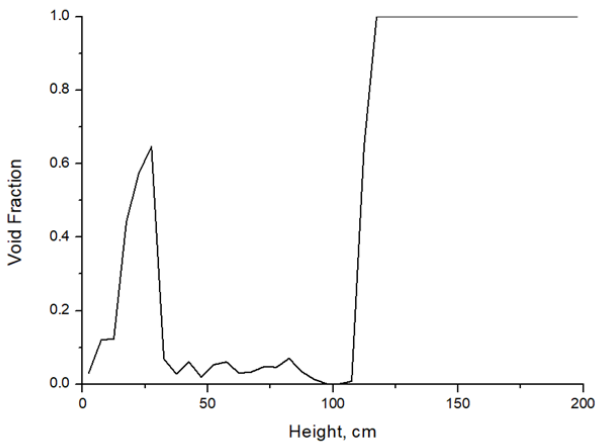

Fig. 4. Axial void fraction distribution at the time of triggering in KS-4 simulation

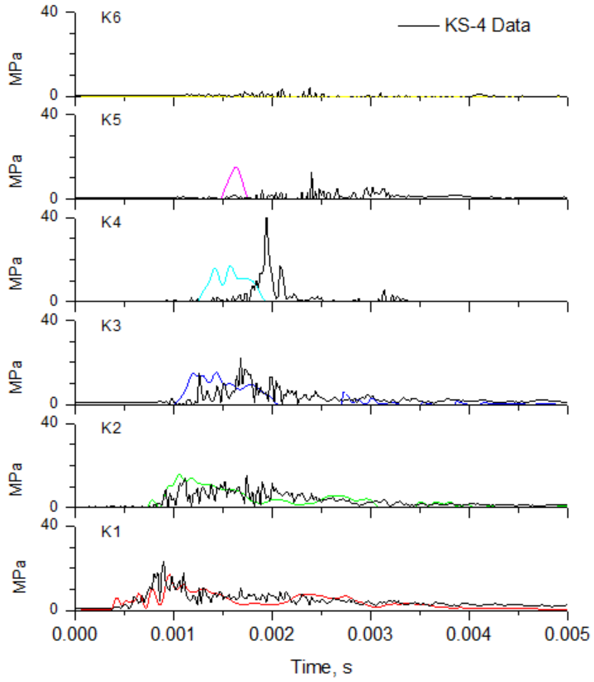

Fig. 5. Explosion pressure traces in KS-4 simulation

3.2 TROI TS-4

For TS-4 simulation, the initial jet speed of 2.46 m/s at the elevation of 1.6 m was chosen which best fits the initial melt trajectory in air space. The jet diameter was the same as reported from the experiment. One unique feature of TS-4 test is that the initial jet coming out of the nozzle was not a coherant cylidirical jet, but a spray-shape for up to a half a second.

The melt jet front locations of two different cases, coherent cylindrical jet and sprayed (multi-jet of smaller particles of 3 mm diameter for initial 0.3 s), are compared in Fig. 6 together with experimental data. It shows that in the single jet case fuel falls much faster in water pool than the test data. But when in the initial 0.3 s, 3 mm pre-broken particles are injected, the fall pattern looks much closer to the test data.

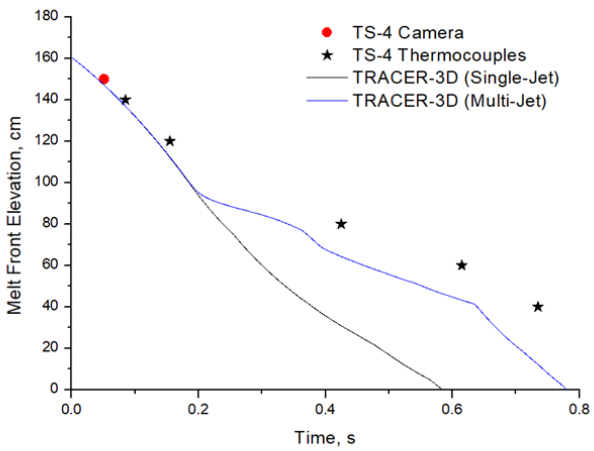

Fig. 6. Jet front elevation in TS-4 simulation

Explosion triggering in TS-4 calculation was also made by applying 15 MPa to the triggering cell at the time of triggering. The void fraction of coolant at the time of triggering is shown in Fig. 7. It is generally low because the coolant is subcooled by 60ºC except the middle section where it is ~0.7.

The explosion traces are compared with the experimental data in Fig. 8. The general trend of the explosion propagation is acceptable, although the magnitude of peak pressure is underestimated.

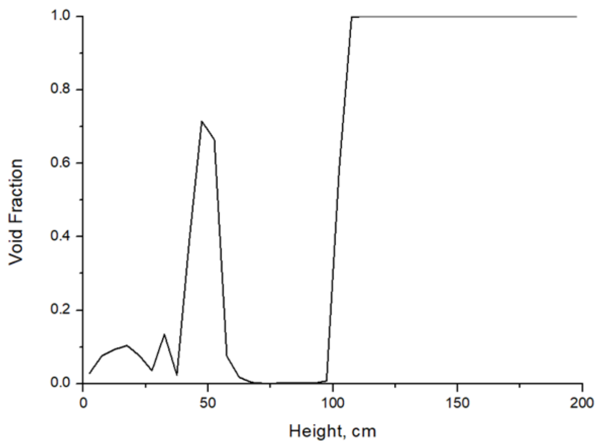

Fig. 7. Axial void fraction distribution at the time of triggering in TS-4 simulation

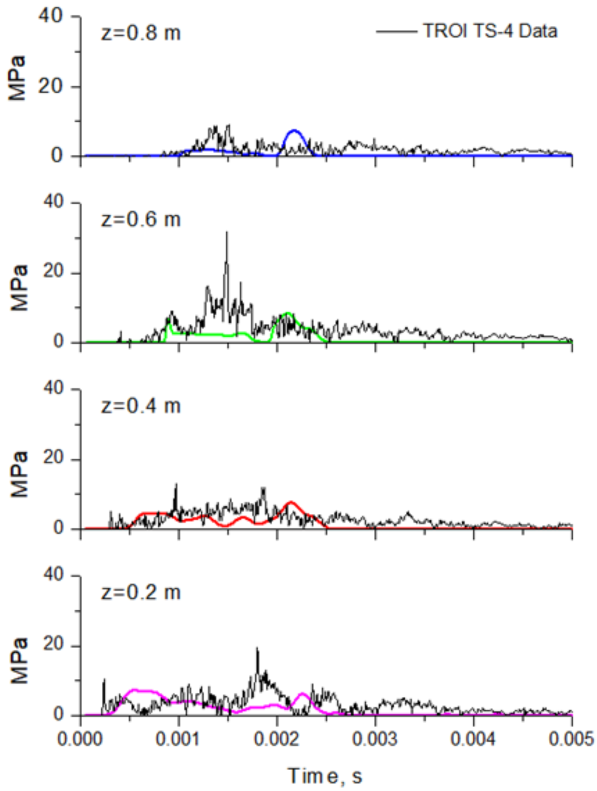

Fig. 8. Explosion pressure traces in TS-4 simulation

4. Conclusion

Three-field, three-dimensional computational model for fuel-coolant interactions, TRACER-3D, has been developed and the validation calculations were carried out. Simulations of KROTOS KS-4 and TROI TS-4 tests showed an excellent performance in mixing phase, despite of very complex and conjugate nature of FCI mixing phenomenon encompassing fuel breakup, evaporation, and multiphase flow regime. It is also observed that corium interaction with subcooled water by 60ºC still results in high local void fraction, which may retard the explosion propagation. The code will be used eventually in investigating three dimensional characteristics of FCIs in in-vessel and ex-vessl.

Acknowledgments

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