

Assessment of Dimensional Effects in Fuel-Coolant Interaction Analysis

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1. Introduction

Fuel-Coolant Interaction (FCI) refers to the interaction between molten fuel and the surrounding coolant that may occur during a severe nuclear reactor accident. Owing to its potentially explosive nature, FCI poses a significant threat to the integrity of reactor containment structures. To assess plant safety under such conditions, a number of computational tools have been developed. Notable examples include TEXAS, which employs one-dimensional Lagrangian–Eulerian coupling [1]; MC3D, which applies three-dimensional Eulerian four-field modeling [2]; and TRACER-II, which implements two-dimensional Eulerian four-field modeling [3]. A three-dimensional Lagrangian–Eulerian coupled FCI code, TRACER-3D, has recently been developed [4].

In general, one-dimensional codes, such as the TEXAS code, offer the advantages of reduced computational storage requirements and shorter execution times. Multi-dimensional codes, on the other hand, demand greater computational resources and longer computing times. Nevertheless, an important question arises that a one-dimensional approach is sufficient when the problem of interest exhibits inherently multi-dimensional characteristics, as in the case where a molten fuel jet with a diameter of several tens of centimeters falls into a water pool several meters in diameter.

In FCI analysis, one of the key dimensional effects is associated with the void fraction of the coolant vapor. Heat transfer and fluid flow models are strongly influenced by the so-called two-phase flow patterns, which are primarily determined by the void fraction. However, a one-dimensional code cannot resolve the local distribution of void fraction; instead, it provides only an averaged value over the cross-sectional area of the computational domain.

In this study, the dimensional effects in fuel-coolant interaction analysis are assessed by comparing the results of identical problems calculated using the TEXAS-VI and TRACER-3D codes. Both codes employ a Lagrangian–Eulerian approach; however, their dimensionality differs: TEXAS-VI is a one-dimensional code, whereas TRACER-3D is three-dimensional. Two problems were selected for this comparison: the KROTOS KS-4 test and an ex-vessel steam explosion in a PWR cavity.

2. KROTOS KS-4 Calculations

Past FCI experiments employing real corium melt are limited to a few notable cases, including the FARO, KROTOS, and TROI experiments. More recently, the OECD/NEA SERENA project supported additional KROTOS and TROI tests [5]. Among these, the KROTOS KS-4 test was selected for the present calculations. The key experimental conditions of the KS-4 test are summarized in Table 1.

Table 1. Test conditions of KROTOS KS-4

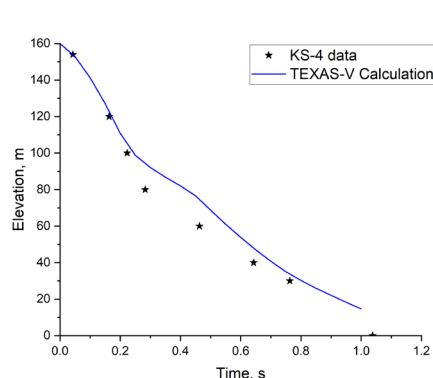
Parameter	KROTOS KS-4
Melt comp.	UO ₂ (80):ZrO ₂ (20)
Melt mass, kg	3.21
Melt temp., K	2963
Jet dia., cm	3.0 (2.16)*
Free fall, m	0.5
Water depth, m	1.1
Water temp., K	332
Pool dia., m	0.2
Pressure, bar	2.1
Jet speed, m/s	2.3 (1.6)*
Trigger time, s	1.04

*(): Adjusted input values for simulation

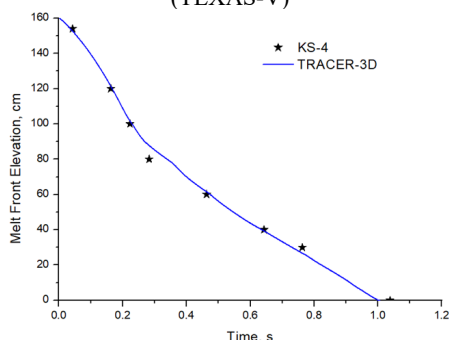
It should be noted that, in the KS-4 simulation, the initial jet velocity was adjusted to 1.6 m/s in order to reproduce the free-fall trajectory in air, and the jet diameter was also modified to ensure that the total melt mass poured were same.

Fig. 1 shows the comparison of fuel leading edge location calculated by TEXAS-VI and TRACER-3D. In the free fall space down to water surface at the elevation of 110 cm, both predictions look good at reproducing free fall trajectory. When it enters water pool, the fuel jet as well as large fuel particles break up as it falls through water pool. The TEXAS-VI prediction shows more deceleration than that of TRACER-3D at the early stage in water pool. Also, in TEXAS-VI simulation the fuel did not reach the bottom until the triggering. In general, the prediction of fuel front location is good, despite of very complex and conjugate nature of fuel mixing phenomenon encompassing fuel breakup, evaporation, and multiphase flow regime.

Void fraction profiles at the time of triggering are shown in Fig. 2. It is noted that the void fraction calculated by TEXAS is the average value over horizontal plane since the code is one-dimensional. The void fraction profile from the TRACER-3D is for the centerline cells. In TRACER-3D, the number of meshes on horizontal plane were 5 by 5. Obviously, the centerline void fractions were much higher than the

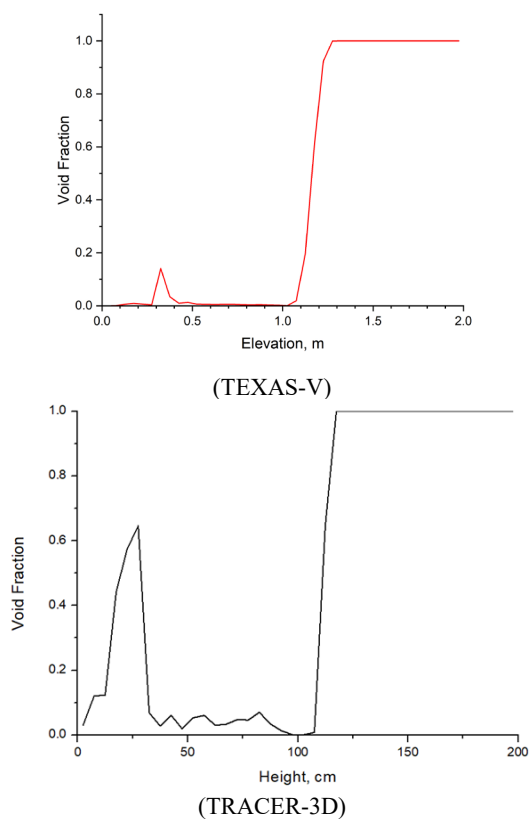


(TEXAS-V)

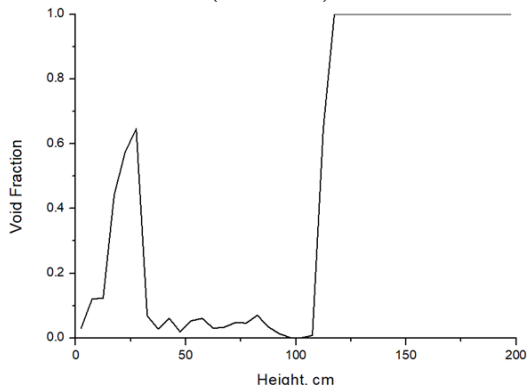


(TRACER-3D)

Fig. 1. Fuel front elevation during mixing in KS-4

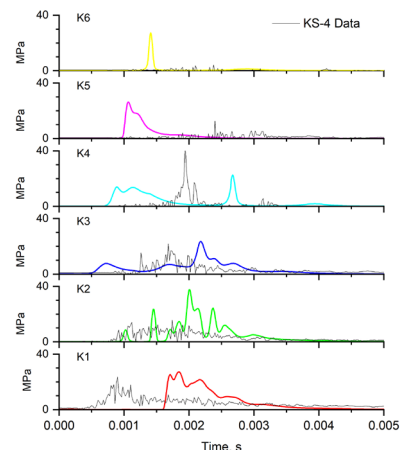


(TEXAS-V)

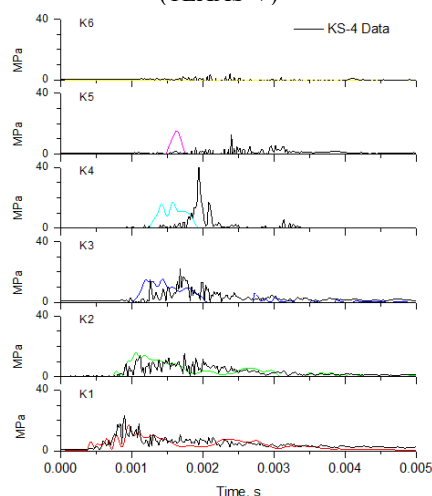


(TRACER-3D)

Fig. 2. Axial void fraction distribution at the time of triggering in KS-4 (center cells in TRACER-3D)



(TEXAS-V)



(TRACER-3D)

Fig. 3. Explosion pressures in KS-4

average values over the horizontal plane. This difference can be one of the dimensional effects in the FCI analysis.

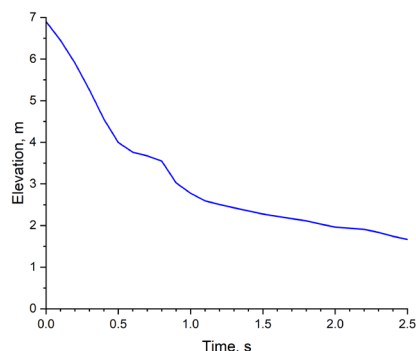
Triggering of explosion was made by applying 15 MPa to the triggering cell at the time of triggering (1.04 second). The explosion pressures are compared with the experimental data in Fig. 3. It looks odd that in TEXAS calculation the first explosion pressure appeared in the middle of test section and then propagated both upward and downward directions.

3. Ex-Vessel FCI in PWR Cavity

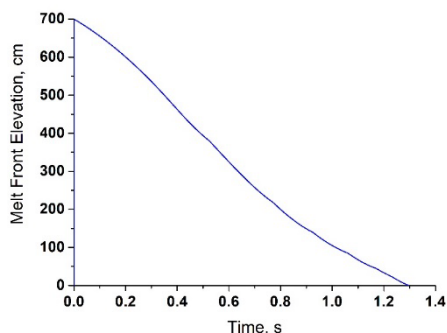
In a typical ex-vessel steam explosion occurring in a large PWR cavity, the fuel jet diameter is on the order of several tens of centimeters, whereas the cavity diameter extends to several meters. This dimensional disparity suggests that the radial extent of the fuel-coolant mixture can be significantly smaller than the cavity radius. Accordingly, it is of interest to compare one-dimensional and multi-dimensional analyses. For this study, a simple rectangular geometry was selected to represent the reactor cavity, with the cavity dimensions and initial conditions summarized in Table 2.

Table 2. Initial and Boundary Conditions of Ex-Vessel
FCI in PWR Reactor Cavity

Parameter	Value
Reactor vessel outer diameter	4.8 m
Cavity side	6.5 m
Cavity height	7.0 m
Melt injection height	7.0 m
Water pool depth	5.0 m
Cavity pressure	2.0 bars
Coolant temperature	343 K (50 K sub)
Melt jet diameter	0.3 m
Melt temperature	3223 K (300 K sup)
Mesh size	$\Delta x = \Delta y = \Delta z = 50$ cm



(TEXAS-V)

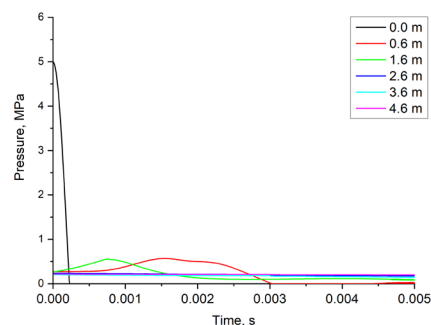


(TRACER-3D at wall)

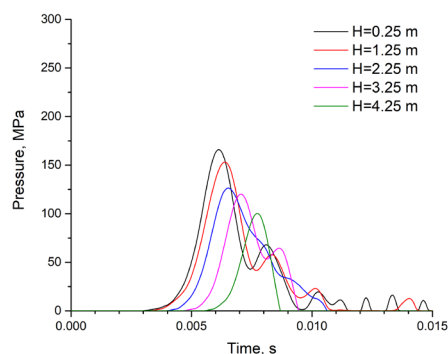
Fig. 4. Fuel front elevation during mixing

In the TEXAS-VI calculation, the fuel did not reach the cavity bottom but remained suspended at an elevation of about two meters above it, as shown in Fig. 4. This behavior may be attributed to the large number of particles assigned to each parcel, which caused the computational cells to become overpacked. This issue will be addressed, and the section will be revised once updated results are available. In contrast, the TRACER-3D calculation showed that the fuel reached the bottom within approximately 1.3 seconds.

Explosion calculations were performed with triggering at the bottom of the cavity at the time of fuel reaching the bottom. The explosion pressures are shown in Fig. 5. Since the fuel did not reach the bottom in TEXAS-VI calculation, the explosion was not triggered properly as shown in Fig. 5. Meanwhile, the TRACER-3D calculation showed the peak pressure at wall



(TEXAS-V)



(TRACER-3D at wall)

Fig. 5. Comparison of explosion pressures

exceeded 150 MPa, which is considered very high pressure. The explosion calculations will be also revised after the unrealistic behavior of mixing calculation with TEXAS-VI.

Explosion calculations were performed by initiating the trigger at the bottom of the cavity when the fuel reached the bottom. The resulting explosion pressures are presented in Fig. 5. In the TEXAS-VI calculation, however, the fuel did not reach the bottom, and thus the explosion was not properly triggered, as shown in the figure. In contrast, the TRACER-3D calculation predicted that the peak wall pressure exceeded 150 MPa, which is regarded as extremely high. These explosion calculations will be revised once the unrealistic mixing behavior observed in the TEXAS-VI results is corrected.

4. Conclusion

In this study, the dimensional effects in fuel-coolant interaction analysis are assessed by comparing the results of identical problems calculated using the TEXAS-V and TRACER-3D codes. Both codes employ a Lagrangian-Eulerian approach; however, their dimensionality differs: TEXAS-V is a one-dimensional code, whereas TRACER-3D is three-dimensional. Two problems were selected for this comparison: the KROTOS KS-4 test and an ex-vessel steam explosion in a PWR cavity.

The KROTOS KS-4 calculations demonstrated reasonably good agreement with the experimental data in both TEXAS-VI and TRACER-3D, except for a

noticeable discrepancy in the void fractions. However, an unrealistic behavior was observed in the TEXAS-VI calculation, and the comparison will be finalized once this issue is corrected.

Acknowledgments

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