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Effects of Water Pool Depth for Ex-Vessel Molten Core Coolability and Steam Explosion Loads

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1. Introduction

During a severe accident of light water reactors (LWRs), the molten and relocated core is the primary heat source that governs the accident progression. Thus, the coolability of the molten core is the crucial factor for accident mitigation measures. In pressurized water reactors (PWRs), it is likely that water exists in the reactor cavity when the molten core drops there after melting through the reactor lower head. It is expected that the water pool enables effective melt breakup through a mild mode of fuel-coolant interactions (FCIs) and it helps the cooling. However, there is also a concern on energetic mode of FCIs, i.e. steam explosions.[1,2]

In our previous work [3], we used an FCI simulation code, JASMINE [4], developed at Japan Atomic Energy Agency (JAEA) for sensitivity and probabilistic analysis of steam explosions, and presented a significant influence of the water pool depth on the energetics. It showed that the steam explosion load is significantly reduced in a shallow water pool due to the limited space for melt jet breakup and premixing. On the other hand, the reduced depth of the pool may adversely influence the coolability of the melt.

This work presents analyses on relatively slow melt jet breakup and cooling behavior with a modified version of JASMINE with additional models necessary for this purpose. The validation of the modified code by referring experimental data is to be presented elsewhere. [5] The present analysis is on the melt jet breakup and coolability in a geometric and thermohydraulic conditions assuming APR1400, a Korean advanced type of PWR. We examined influences of important model parameters and initial/boundary conditions with special emphasis on the water pool depth. The effects of the pool depth on both aspects of the phenomena, coolability and steam explosion energetics, are discussed.

2. JASMINE Model Extension

Additional models implemented in JASMINE code included the size distribution of melt particles produced by jet breakup, a simple model for consideration of non-local radiation heat transfer beyond the grid, and an

Table I: Geometry and accident condition relevant to APR1400 severe accident

Radius of the reactor vessel (m)	2.5
Depth of the reactor cavity (m)	6.5
Area of the cavity floor (m^2)	80
Free volume of the containment (m^3)	94700
Mass of molten core (t)	120-145
Molten core temperature (K)	2900-3300
Containment pressure (MPa)	~0.19
Water level in the cavity (m)	1-6
Water temperature (K)	~300

Table II: Model parameters and initial/boundary conditions

Parameter	Base case (BC) value	Modified value	Case ID
Factor for jet breakup length*1, C_{ent}	1	0.7 / 1.5	JB1 / JB2
Factor for particle size*2, C_{dmm}	1	0.7 / 1.5	PS1 / PS2
Factor for heat transfer*3, C_{htc}	2	1 / 4	HT1 / HT2
Melt initial temperature (K), T_j (Superheat)	3010 (170)	3300 (460)	MT
Melt jet diameter (m), D_j	0.2	0.5	MD
Melt jet velocity (m/s), V_j	6	12	MV
Water temperature (K), T_l (Subcool)	300 (92)	350 (42)	WT
Water level (m), H_p	5.9	1.1~7.9	WLa~WLe

*1 Modifies the melt stripping mass flux on the jet surface (larger values make shorter jet breakup lengths)
*2 Modifies the mass median diameter of particles *3 Modifies heat transfer coefficients for particles

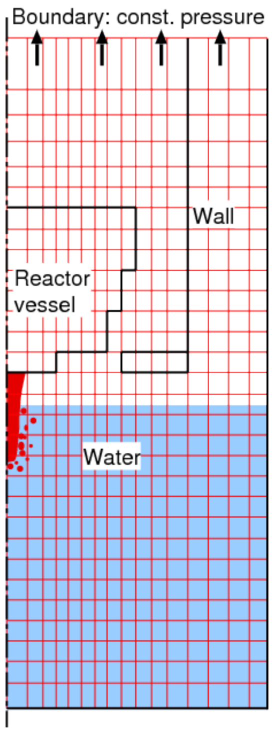

Fig. 1: Analytical grid for the simulation of APR1400 ex-vessel melt jet breakup and cooling

improved treatment of the settled melt particles. The particle size distribution was assumed mono disperse in the assessment of steam explosion loads and handled parametrically with a concept of bounding or by considering the uncertainty range. For the coolability assessment, however, its direct impact on the heat transfer surface area increases the significance. We adopted an empirical correlation developed by Moriyama et al.(2005) [6]. Other two models are remedies on numerical problems observed in simulations of relatively long term phenomena.

3. Analytical Condition

The geometric information for the containment vessel and the reactor cavity of APR1400 was obtained from Kim et al.(2005) [7] and Park et al.(2011) [8]. The thermohydraulic conditions during various severe accident sequences in APR1400 were found in Rempe et al.(2005) [9] and Ahn et al.(2011) [10].

Based on such information as summarized in Table I, an analytical model was made as shown in Fig. 1 and input variables were set as summarized in Table II (values for base case). The actual geometry of the reactor cavity is asymmetric. It was modeled in 2D cylindrical domain by preserving the floor area, $80m^2$, for it is important as the area available for melt spreading or particle bed accumulation. The melt mass and temperature in the reactor vessel lower head prior to the vessel melt through were 120~145t and 2900~3300K, respectively, based on the analysis of SBO with loss of feed water and small to middle LOCA sequences [9,10]. The initial diameter and the velocity of melt jet are important because they comprise the flow rate, i.e. the heat input rate. Also, the jet breakup length, the water depth required for complete breakup of the jet, is proportional to the jet diameter. The diameter was assumed 0.2m in the base case considering the suggestion in Rempe et al. [9] that the failure of the lower head is likely to be partial creep. The velocity was given from the static head of the melt in the vessel and expected low back pressures; depressurization is expected even in high pressure scenarios due to creep rapture of pressurizer surge line by hot steam flow.

We examined influences of the input variables as listed in the 3rd column of Table II. Those cases are named and referred hereafter as in the 4th column. The first 3 rows are model parameters and the others are initial/boundary conditions.

3. Results

3.1 Melt breakup and coolability

The discharge of the melt of ~145t under the assumed condition in the base case takes 95s.The cases with larger melt flow rates, MD (large jet diameter) and MV (higher initial velocity) give 47 and 15s, respectively. The results of simulations up to 20s showed almost constant heat exchange rates between the melt and water for constant melt inlet flow rates, that suggest a quasi steady state heat transfer structure was established during the time scale of melt discharge.

Based on this observation and considering the computational resources, we ran simulations till 20s and examined the melt cooling performance in the quasi steady state with quenching ratio as an index, that was defined as the ratio of the heat released from the melt and the enthalpy brought into the system by the melt with the base temperature at the solidus point of the melt, 2840K. Values of this index more than 1 means the situation the melt is in average frozen.

Figure 2 shows the history of the quench ratio up to 20s for every case, and the influence of model parameters (a) and that of initial/boundary conditions (b). The plots showed quick increase in the initial ~2s and slow increase after 5s. The latter is attributed to the establishment of the quasi steady state heat removal structure. Most of the cases including the base case showed values more than 1 at 20s. Two cases of shallow water pool, WLa and WLb showed values less than 1, meaning still molten state in average.

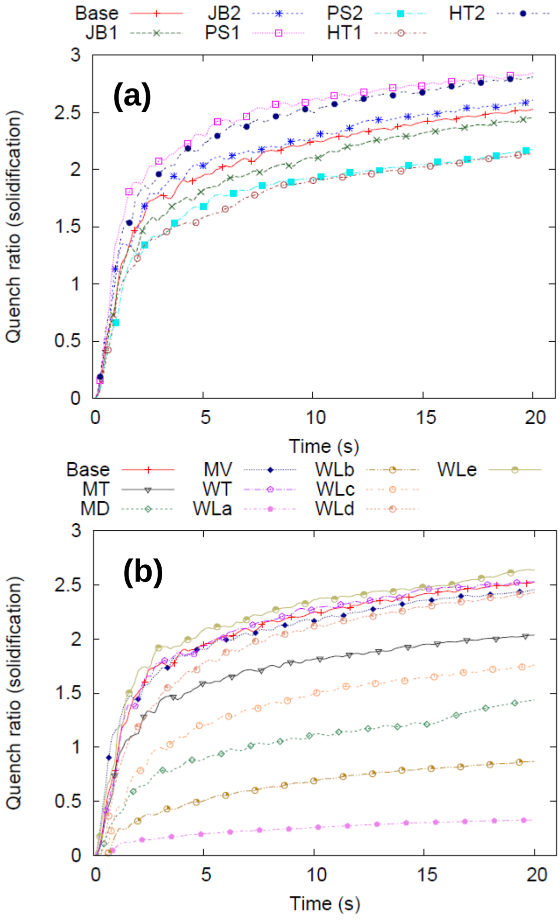

Fig. 2: Quench ratio in terms of solidification; (a) influence of model parameters, (b) influence of initial/boundary conditions

Figure 3 compares the results at 20s among cases for the quench ratio (a) and two other variables, the fraction of melt pool (molten or solidified continuous body on the floor) (b) and the average enthalpy of the melt pool (c).

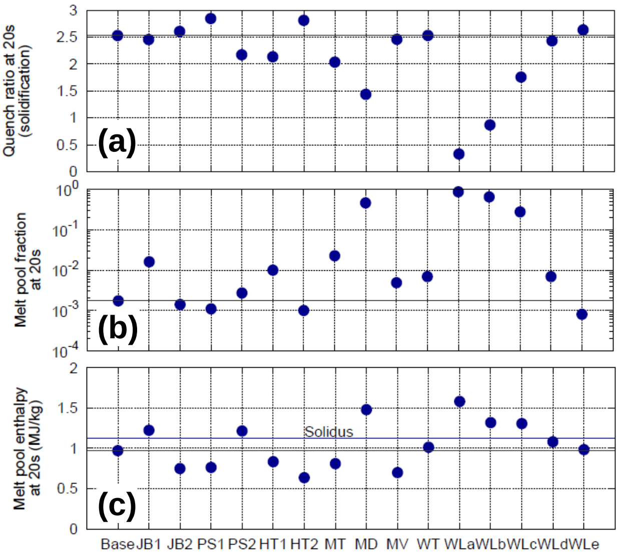

Fig. 3: Comparison of the results at 20s among cases ; (a) quench ratio, (b) melt pool fraction, (c) melt pool enthalpy

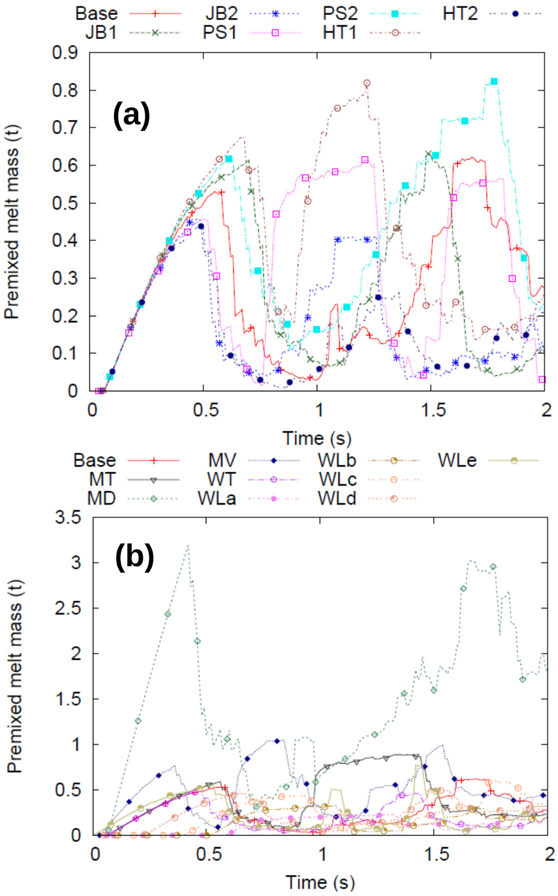

Fig. 4: History of the premixed mass of melt (molten mass in the less void zone, α<0.75); (a) influence of model parameters, (b) influence of initial/boundary conditions

The comparison shows that the influence of initial/boundary conditions is much stronger than that of the model parameters. Though the quench ratio (a) indicates the whole melt was solidified in average in all the cases except the two shallowest pool cases, it is found in (c) that the melt pool was molten for the cases JB1, PS2, MD, WLa~WLc. For MD and WLa~WLc, more than 1% of the melt formed molten pool (Fig. 3 (b) and (c)).

3.2 Effects of Pool Depth on Steam Explosions

Steam explosion loads can be estimated based on the correlation of the "premixed mass", defined by the authors [3] as the mass of the molten material in less voided zone (void fraction <0.75). The previous work [3] adopted a method of steam explosion assessment in which the triggering of steam explosion was assumed at the time of the first peak of the premixed mass and showed that it gave nearly the maximum kinetic energy from a given sequence of premixing event. The premixed mass evaluated in the present calculations is shown in Fig. 4. Every case showed oscillation of the premixed mass mainly due to the void generation and escape in the mixing zone. The values at the first peaks corresponds to the nearly maximum steam explosion loads under given conditions.

Also, the previous work [3] showed that the energy conversion ratio defined by the ratio of the kinetic energy to the enthalpy of the premixed melt material at the triggering fell in a narrow range around 4%. Figure 5 shows the scattering of the energy conversion ratio in terms of the resulted kinetic energy (a) or in terms of the jet diameter (b). The figure shows the conversion ratio is around 4% for strong explosions, and has dependence on the jet diameter, that indicates about 6% as upper bound for the jets of 0.2m diameter, the condition of the present work.

Figure 6 shows the comparison of the cooling performance indicated by the quench ratio (a), the premixed mass (b) and the kinetic energy (c) estimated by the product of the enthalpy of the premixed mass and the energy conversion ratio, 6%, with the water pool depth as horizontal axis. According to Fig. 3 (c), the cases of water pool depth below 3.1m (WLc) had molten pool at 20s. Attenuation of the steam explosion energy is observed in the same range of the pool depth. This result implicates that when the pool depth is enough for complete melt breakup and cooling (solidification), the possible upper bound steam explosion load reaches the maximum in the given geometry and condition.

Then, as long as we want to make the complete melt breakup and cooling available, we can not expect the attenuation effect of the steam explosion load by limiting the water depth, and we need to prepare for the possible steam explosion with strong enough structures or by other means. Or, we can expect the steam explosion attenuation by a shallow pool if we can assure cooling of not broken up melt at the bottom of the cavity.

4. Conclusions

The ex-vessel melt jet breakup and cooling behavior in the condition assuming APR1400 severe accident was simulated with a modified version of JASMINE code. Influences of 3 model parameters and 5 initial/boundary condition variables were examined. The influence of initial/boundary conditions, especially of the water pool depth, was much stronger than that of model parameters.

The effect of the water pool depth was examined with special emphasis in terms of the contradictory demands for securing enough melt jet breakup and cooling and attenuation of steam explosion loads.

The results showed there is no condition that satisfies both demands. If complete melt jet breakup is wanted, we need to prepare for the steam explosion loads. If attenuation of steam explosion by a shallow pool is wanted, we need to prepare cooling facility for not broken up melt reaching the floor.

ACKNOWLEDGEMENTS

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REFERENCES

[1] OECD/NEA, OECD workshop on ex-vessel debris coolability summary and recommendations, NEA/CSNI/R(2000)14, 2011.

[2] OECD/NEA. OECD research program on fuel-coolant interaction: steam explosion resolution for nuclear applications–SERENA, final report. Technical Report NEA/CSNI/R(2007)11, OECD/NEA/CSNI, 2007.

[3] K. Moriyama, et al., Probabilistic distribution of ex-vessel steam explosion loads influenced by the uncertainties in the initial/model parameters including water level for the case of the IVR failure in a typical PWR, NTHAS9: The 9th Symposium on Nuclear Thermal Hydraulics and Safety, Buyeo, Korea, (N9P0007), 2014.

[4] K. Moriyama et al., Steam explosion simulation code JASMINE v.3 user's guide, JAEA-Data/Code 2008-014, 2008.

[5] K. Moriyama, H.S. Park, M.H. Kim, Simulation of melt jet breakup and coolability experiments with JASMINE code, ICONE23: 23rd International Conference on Nuclear Engineering, Makuhari, Japan, (ICONE23-1672), 2015 [To be presented].

[6] K. Moriyama et al., Coarse break-up of a stream of oxide and steel melt in a water pool, JAERI-Research 2005-017, Japan Atomic Energy Research Institute, 2005.

[7] J.T. Kim et al., A study on the hydrogen behavior and its mitigation in the APR1400 containment during a severe accident, KAERI/TR-2948/2005, Korea Atomic Energy Research Institute, 2005.[In Korean]

[8] J.H. Park et al., MCCI simulation for the APR-1400 TLOFW sequence, Transactions fo the Korean Nuclear Society 2011 Spring Meeting, Taebaek, Korea, 2011.

[9] J. Rempe et al., In-vessel retention strategy for high power reactors, INEEL/EXT-04-02561, Idaho National Engineering and Environmental Laboratory, 2005.

[10] K.I. Ahn et al., The plant-specific uncertainty analysis for an ex-vessel steam explosion-induced pressure load using a TEXAS-SAUNA coupled system, Nuclear Engineering and Design, vol.249, pp.400-412, 2012.

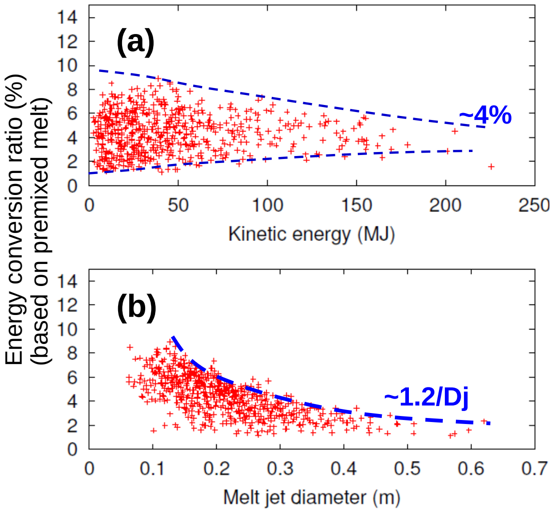

Fig. 5: Scattering of the energy conversion ratio of steam explosions in terms of the premixed mass on the water pool depth in a random sampling analysis for input variables by LHS; (a) dependence on the kinetic energy, (b) dependence on the melt jet diameter (Moriyama et al. [3])

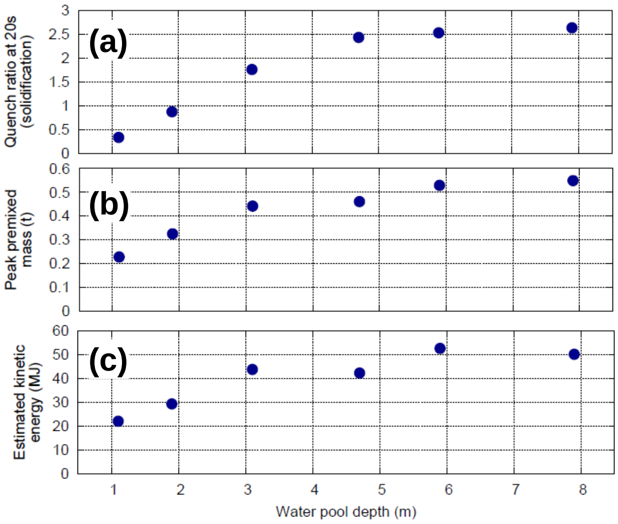

Fig. 6: Comparison of the influence of the water pool depth on the quench ratio (a), peak premixed mass (b) and the estimated steam explosion kinetic energy (c)