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Analysis of ex-vessel melt jet breakup and coolability. Part 1: Sensitivity on model parameters and accident conditions

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HIGHLIGHTS

- Application of JASMINE code to melt jet breakup and coolability in APR1400 condition.
- Coolability indexes for quasi steady state breakup and cooling process.
- Typical case in complete breakup/solidification, film boiling quench not reached.
- Significant impact of water depth and melt jet size; weak impact of model parameters.

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ABSTRACT

The breakup of a melt jet falling in a water pool and the coolability of the melt particles produced by such jet breakup are important phenomena in terms of the mitigation of severe accident consequences in light water reactors, because the molten and relocated core material is the primary heat source that governs the accident progression. We applied a modified version of the fuel–coolant interaction simulation code, JASMINE, developed at Japan Atomic Energy Agency (JAEA) to a plant scale simulation of melt jet breakup and cooling assuming an ex-vessel condition in the APR1400, a Korean advanced pressurized water reactor. Also, we examined the sensitivity on seven model parameters and five initial/boundary condition variables. The results showed that the melt cooling performance of a 6 m deep water pool in the reactor cavity is enough for removing the initial melt enthalpy for solidification, for a melt jet of 0.2 m initial diameter. The impacts of the model parameters were relatively weak and that of some of the initial/boundary condition variables, namely the water depth and melt jet diameter, were very strong. The present model indicated that a significant fraction of the melt jet is not broken up and forms a continuous melt pool on the containment floor in cases with a large melt jet diameter, 0.5 m, or a shallow water pool depth, $\leq$3 m.

1. Introduction

In a severe accident of light water reactors (LWRs) with significant core damage and melt down, the molten and relocated core material is the primary heat source that governs the accident progression. In view of accident mitigation and termination, cooling the molten core material is the ultimate requisite to stop further progress of plant damages, while confinement of the radioactive fission products within a predefined boundary, e.g. the containment vessel, is also crucial for the mitigation of the radiological impacts to the public and environment. Thus, the severe accident management (SAM) measures for cooling of the molten core in the containment vessel make the final defense boundary for both stopping the accident progression and confining the radioactive materials.

Except the cases that so-called dry-cavity strategy is taken, it is likely that the molten core drops into a water pool in the reactor cavity that is prepared as a SAM action or as a result of leakage from the reactor cooling system (RCS). Therefore, it is highly concerned whether the molten core in such conditions is broken up into small particles and makes a coolable debris bed or makes an agglomerated melt lump that might lead to inefficient cooling and the molten core concrete interaction (MCCI) (OECD/NEA, 2000; Bürger, 2006). The ex-vessel melt cooling process consists of three steps: (1) the melt jet discharge from the reactor vessel (RV) and breakup/cooling followed by debris bed formation, (2) cooling

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of the settled particulate debris bed or a continuous molten/solid lump by boiling and natural convection, and (3) cooling of the molten core on the containment floor in the situation of molten core concrete interaction (MCCI). The outcomes of upstream steps determine the initial/boundary condition of the following steps.

The breakup of the molten core discharged from the RV as a jet, the first step, has been intensively studied in the last a few decades. In a large part of the previous research works, the phenomenon was focused on as the premixing phase of energetic steam explosions, the practical time frame of which was up to a few seconds (Yamano et al., 1996; Alsmeyer, 2000; Bürger et al., 2010). Large scale fuel–coolant interaction (FCI) experiments have been performed and provided data on the melt jet breakup, heat transfer, the resulting debris particle sizes, debris bed geometry, and so on, with various melt materials including prototypic UO_2–ZrO_2 mixtures (corium), other oxide materials and metals, e.g. FARO (Magallon et al., 1999; Magallon and Huhtiniemi, 2001; Magallon, 2006), PREMIX (Kaiser et al., 2001), ALPHA/GPM (Moriyama et al., 2005). Relatively limited information is found in those previous works for the characterization of resulted debris beds. The DEFOR series of experiments (Kudinov et al., 2010, 2015) with various binary oxide mixtures recently provided additional information, i.e. debris bed porosity and particle morphology.

Several computer codes based on multiphase flow modeling methods were developed for the simulation of FCIs including the steam explosion. Those codes have been compared and tested through two major cooperative analytical exercises held under the Nuclear Energy Agency of Organization for Economic Co-operation and Development (OECD/NEA), namely the International Standard Program No. 39 (ISP39) (1996–1997) (Annunziato et al., 1998) and Steam Explosion Resolution for Nuclear Applications (SERENA) program (Phase 1: 2002–2005, Phase 2: 2007–2012) (OECD/NEA, 2007, 2015). Meignen et al. (2005) and more recently Meignen et al. (2014) provided comprehensive review of such codes and models. The summary report of SERENA Phase 2 (OECD/NEA, 2015), concluded that those codes were shown to be able to give results in fair agreement with available steam explosion experimental data, and to give plant scale assessment results consistent among the codes. A limitation of the SERENA program was the range of conditions: a single jet of oxidic corium melt falling into the center of a water pool; real accidents may have different conditions, i.e. metal rich melts and/or off-center fall of the melt. During the SERENA program, the importance of melt solidification during the premixing stage was recognized as a primary limiting mechanism of the steam explosion energy for corium, and additional models including the size distribution of the melt droplets, surface solidification were developed in some codes, e.g. MC3D (Uršič et al., 2012; Meignen et al., 2014), TEXAS (Chen et al., 2013). Note that the cooling and solidification behaviors for individual melt droplets of different sizes are more easily implemented in Lagrangian models, and those having such models already included solidification models, e.g. JASMINE (Moriyama et al., 2008), JEMI (Schröder et al., 2009).

The second and third steps of the whole process have been approached by different experimental and analytical methods. Limiting the discussions to analytical works, the cooling performance of settled debris bed represented by the dry out heat flux (DHF) was analyzed by multiphase flow based models or CFD tools (Bürger et al., 2006; Takasuo et al., 2014) handling the flow and heat transfer in porous media with porosity and permeability. The debris cooling during the MCCI was simulated by dedicated models (Strizhov et al., 1996; Zhong, 2011; Maruyama et al., 2006; Robb et al., 2014), that are also partially included in system-level severe accident simulation codes (e.g. Gauntt et al., 2005).

So far, the assessment for the second and the third steps were based on presumed initial conditions such as a wet or dry debris bed, dry contact of the molten core and concrete base mat, and so on. There is a broad gap between the assumed initial conditions of the particulate debris bed and the MCCI. The preceding transient process of the melt jet breakup and debris bed formation can lead to variety of initial conditions for the debris bed cooling process, and influence the conditions for the MCCI as well. At least, the fraction of particulate debris and continuous lump, either solid of melt, and also the particle size, porosity and permeability distribution in the debris bed are of significant interest. This transient phase of middle range time frame, remaining as a gap between the research topics of steam explosions and debris coolability, can be tackled by extending the availability of existing FCI simulation codes. This area has been worked on only recently (Kudinov et al., 2012; Pohlner et al., 2014). Such an analytical study on the plant scale phenomena including the sensitivity and uncertainty in terms of various input variables has not been done.

JASMINE (Moriyama et al., 2008) is an FCI simulation code developed at Japan Atomic Energy Agency (JAEA) and available at OECD/NEA Dababank. It has been validated to some extent for the assessment of steam explosion energetics partially through the above mentioned cooperative analytical exercises. However, its application to long term melt jet breakup and cooling behavior has not been tested comprehensively.

For the steam explosion assessment, simplification and parametric bounding or conservative approaches were taken in some aspects of melt jet breakup and heat transfer models (Moriyama and Park, 2015). In our recent work (Moriyama and Park, 2016), we introduced additional models into JASMINE including an empirical model for the melt particle size distribution, radiation heat transfer beyond analytical cell boundaries and so on, since such models were considered more significant in simulating the melt jet breakup and cooling behavior for longer time frame, up to tens of seconds. The modified code was tested by simulating experiments.

In this work, we applied the modified version of JASMINE to the plant scale simulation of the ex-vessel melt jet breakup and cooling in a geometry assuming the APR1400, an advanced pressurized water reactor developed by Korea Electric Power Corporation (KOPEC) and Korea Hydro and Nuclear Power Company (KHNP), being constructed as Shin-Kori units 3 & 4 in Korea and Barakah units 1 & 2 in the United Arab Emirates (UAE) (as of 2015) (KHNP, 2011), and attempted to clarify the consequences of the melt jet breakup and sedimentation transient in terms of the coolability in a realistic condition. Also, influences of input variables related to model parameters and initial/boundary conditions were examined. Indexes characterizing the coolability during a quasi steady state melt discharge process were proposed and used for comparison of the results. This work comprises the first part of a series of two papers, and covers the problem definition, base case results and a sensitivity analyses. The second piece will be dedicated to an uncertainty analysis with probabilistic framework (Moriyama et al., 2016).

2. JASMINE code and additional models

Fig. 1 shows the concept of melt jet breakup modeling in JASMINE. The model consists of a two-phase flow solver and a set of melt models including a vertical one dimensional jet, Lagrangian grouped particles and a radial one dimensional pool. The melt pool model accommodates a molten pool or solidified continuous lump on the floor. All those models are configured for 2D cylindrical geometry. The heat transfer from the high temperature melt is mainly carried by the particle model for it has most of the surface area of the melt. Liu and Theofanous (1996) correlation for film boiling on spherical particles and the Stefan–Boltzmann law for radiation heat transfer are used as the most important models in this aspect.