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Sensitivity and uncertainty analyses of ex-vessel molten core cooling in a flooded cavity during a severe accident

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ABSTRACT

Sensitivity and uncertainty analyses of molten core cooling under the ex-vessel phase of a severe accident of a light water reactor was performed with the COOLAP-I (COOLability Analysis Program-I) model, a parametric model considering one-dimensional heat transfer of a porous debris particle bed, covering a broad range of phenomena from the melt jet release to the long-term cooling process. COOLAP-I improved the previous version by including particle generation by the fuel-coolant interaction (FCI), and internal heat generation by the decay heat. With nine representative input parameters, an uncertainty analysis using Latin hypercube sampling (LHS) method with 300 samples were conducted, and the cooling characteristics such as total enthalpy, maximum temperature, decay heat ratio, and cake (a lump of connected particles) fraction, were examined for the elapsed time of up to 50 h. This analysis demonstrates the impacts of the water pool depth, the jet breakup-related parameters, and the accumulation area of the debris particles on the cake formation by particle agglomeration and analyzes the long-term coolability of debris particle bed in plant scale conditions.

1. Introduction

When a severe accident occurs in light water reactors (LWRs), the molten core slips down into the lower head of the reactor pressure vessel (RPV) (Sehgal, 2011). Since the relocated molten core has decay heat, it can penetrate the vessel and falls into the reactor cavity if the continuous adequate cooling of the molten core is not satisfied. The cooling of ex-vessel molten core is crucial for the mitigation and termination of severe accident progression within the containment, the last boundary for preventing the release of radioactive material to the environment. In some nuclear plants ones in Korea in particular, severe accident management (SAM) adopting the cavity flooding strategy inherently deals with complex thermal-hydraulic phenomena, such as the fuel–coolant interaction (FCI) before the molten-core concrete interaction (MCCI) during the ex-vessel phase (Park et al., 2001). In the FCI phenomenon, the melt jet penetrating RPV interacts with coolant water in the flooded cavity, and the breakup of jet occurs. If the length of melt jet breakup is longer than water pool depth, the melt in liquid phase directly relocates on the basemat concrete of the cavity. On the other hand, in case of the length of melt jet breakup much shorter than the water pool depth, the melt settles down on the cavity bottom with fully-fragmented particles. Although there are still uncertainties on vessel failure with the condition of melt discharge, the flooded cavity is one of the effective melt retention strategy for preventing the vessel failure.

Previous experimental studies related to the ex-vessel core melt coolability, however, showed the formation of particle agglomeration without the solidification of liquid melt. In corium-coolant mixing (CCM) tests using the COREXIT facility (Spencer et al., 1994), the re-agglomeration of particles was found by the limited quenching in the melt jet breakup phenomenon. The particle agglomeration with low porosity (0.3–0.4) was observed in the DEFOR experiments by Royal Institute of Technology (KTH) (Kudinov et al., 2010), which possibly hinders the cooling of the inner region in debris particle bed. In the FARO experiments using prototypical material (UO_2-ZrO_2 80:20 wt% mixture) (Magallon, 2006), an agglomerated lump was formed, even in the case the melt jet breakup length was shorter than the water pool depth. Above results indicate that the agglomerated lump of melt can be formed at the containment floor even under the condition of pre-flooding of the reactor cavity, and the agglomeration of the debris particles would adversely affect the cooling of the core debris.

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Nomenclature

V	volume, m^3
g	gravitational acceleration, m/s^2
A	surface or cross-sectional area, m^2
C	drag coefficient or jet breakup coefficient
L	melt jet breakup length, m
D	jet diameter, m
Δt_t	effective falling time of melt particle, s
$\Delta t_t'$	falling time without two-phase flow effect, s
d	particle diameter, m
c_p	specific heat, J/kg-K
T	temperature, K
t	time, s
k	thermal conductivity, W/m-K
r	radial coordinate or particle radius, m
q	heat flux, W/m^2
h	specific enthalpy, J/kg
Δh_{ex}	normalized excess specific enthalpy
Δh_{sl}	specific enthalpy of fusion, J/kg
$<>$	local volume average
P	operation power, MWth
F	cumulative mass fraction
d_e	absolute size constant
Bo_p	bond number
n	distribution constant
F_{sb},N_{sb}	subcool factors
Δz	thickness of loose particle bed, m

Greek symbol

α	thermal diffusivity, m^2/s
β	normalized time for the effective particle falling time
γ	fitting parameter for the effective particle transit time, m^{-1}
ρ	density, kg/m^3
σ	surface tension, N/m

Subscript

p	melt particle
D	drag
l	liquid (water)
v	vapor
fb	film boiling
r	radiation
sl	solid-liquid or fusion
s	solid phase or shutdown
0	infinite period before shutdown
MM	mass mean
sub	subcooled
lg	liquid-gas
eff	effective
DHF	dryout heat flux

To understand the characteristic of particle agglomeration, the detail mechanism for agglomeration phenomenon is needed, and several relevant numerical and analytical approaches were performed. The agglomeration phenomenon was considered in an IKEJET/KEMIX simulation based on the FARO experiment (Pohlner et al., 2006), while there was no concrete suggestion to resolve the detail mechanism of particle agglomeration. Recently, Hwang et al. (Hwang et al., 2016) suggested an analytical approach on the particle agglomeration and developed an analytical model, COOLAP-0[1], considering the particle heat release during sedimentation and one-dimensional heat transfer for the particulate and agglomerated (cake) parts of a debris particle bed. Based on its brevity, it can be applied for a broad range of the phenomena from melt jet release to debris particle bed cooling process, and this model was tested with the FARO experimental data (Magallon, 2006). In that research, the calculated mass fraction of the cake and the temperature transient on the bottom plate surface agreed well with the experimental data. They suggested the liquid phase sintering is likely to be the mechanism of particle agglomeration forming the brittle solid known as a cake.

A limitation of the COOLAP-0 model is the lack of ex-vessel phenomenon such as fragmented particle size distribution, decay heat, debris particle bed heat removal mechanism and so forth. In addition, the existing models considered only individual phenomenon (Pohlner et al., 2006; Moriyama et al., 2016a; Bürger et al., 2006), which may not clearly explain the coupled thermal-hydraulic phenomena on coolability including the debris particle bed formation by sedimentation of melt particles produced by melt jet breakup, separation of the particulate and cake parts of the debris particle bed, and long term cooling of the debris particle bed with the decay heat.

In this study, the COOLAP-I model was developed to assess the long-term cooling of a debris particle bed in the plant scale, with emphasis on the thermal-hydraulic phenomenon, aiming at explaining the influences of various factors on the ex-vessel debris coolability and related uncertainties. The model covers the process from the melt release from the RPV to the cooling of the particulate and cake debris particle bed, and the MCCI phenomenon is not included. In order to identify the effect of particle agglomeration clearly, the fully-fragmented of melt jet was assumed in the calculation which is similar with the COOLAP-0 model. Some additional models were implemented, such as decay heat and particle size distribution models, to apply the COOLAP-I model into the plant scale condition. The geometrical condition was set by assuming the severe accident conditions in a APR1400 plant, a Korean advanced pressurized water reactor. One-at-a-time sensitivity tests for fifteen input parameters (nine initial/boundary condition parameters and six model parameters) were performed, and nine parameters which have rather large sensitivity were selected as the uncertainty variables. Uncertainty analysis using Latin hypercube sampling (LHS) was performed, and four output variables were picked up (total enthalpy, maximum temperature, decay heat ratio, and cake fraction). Also, the importance analysis of them were examined (Cohen et al., 2013), and finally the dominant parameters and phenomena were identified in respect to the ex-vessel coolability of molten core.

2. COOLAP-I model for plant scale

In order to examine sensitivity and uncertainty analysis using the COOLAP-I model, the model needs to include key thermal-hydraulic phenomena from the melt jet breakup leading to the long-term cooling period. In Section 2.1, a brief description of the COOLAP-0 model (Hwang et al., 2016) based on the FARO experimental data (Magallon, 2006) is included. Based on the original model, some additional models are implemented, such as decay heat and a general particle distribution model as given in Section 2.2.

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[1] COOLAP originally stands for "COOLability Analysis with Parametric fuel–coolant interaction model." Due to the continuous development of the model, the initial model was renamed as COOLAP (COOLability Analysis Program) Version 0, or COOLAP-0. The improved version of the model described in the paper is called to "COOLAP Version I or COOLAP-I."