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Numerical investigation of SIMMER code for fuel-coolant interaction

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ABSTRACT

Fuel-coolant interaction (FCI) is a very complex but important issue in the safety analysis of the severe accidents for nuclear reactors due to the rapid multiple thermos–hydrodynamic activities. Until now, there are still large uncertainties existing in various phases during the FCI process, such as the melt solidification, fragmentation and relocation, film boiling on the melt surface, coolant vaporization and following vapor explosion, and so on. SIMMER-III code was first developed to analyses core disruptive accidents in liquid-metal fast reactors (LMFRs) as an integral numerical tool coupling multiphase thermal hydraulic code with neutron kinetics model, and was demonstrated its reasonable flexibility in some FCI simulations. In this paper, the applicability of the code in simulating the premixing phase of FCI process is verified in comparison with a related jet-type experiment in literature. In addition, the sensitivity analysis on several key parameters of the related models in the SIMMER code was performed to assess the impacts in the simulation of the FCI premix phase. It is expected that the results can provide some numerical experience for the uncertainty analysis of FCI calculation using SIMMER-III code.

Introduction

Fuel-coolant interaction (FCI) is a very complex but important issue in the safety analysis of the severe accidents for nuclear reactors due to the rapid multiple thermos–hydrodynamic activities and serious damage consequence. In the severe accidents, the molten core may penetrate the structure component and interact with coolant, and may produce an energetic steam explosion to destroy the integrity of the vessel or containment. Depending on the amounts of reacted fuel and coolant, FCI process can be divided into four phases: premixing, triggering, propagation and expansion [1]. During the past decades, extensive experimental and numerical efforts focused on the premixing and expansion phases and remarkable progress in phenomenon description and modeling was obtained. For example, Hansson et al. [2] performed a series of small-scale experiments using molten tin or binary oxide mixtures to explore the effect of melt material on vapor explosion. Hohmann et al. [3] conducted the KROTOS experimental study on the melt-coolant premixing and steam explosion phenomena by Al_2O_3/water mixtures. Huber et al. [4] tested the premixing phase and development of the interaction zone with molten alumina.

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In the premixing phase, the characteristics can be summarized as [5].

- Time scale from millisecond to second.
- Melt size scale from millimeters to meters.
- Wide range of temperature and pressure.
- Fragmentation and mixing of multi components.
- Possible chemical reactions which can change the physical properties of melt and coolant.

On the other hand, some computational codes were developed with various levels of complexity and applied in the FCI simulation. For instance, 1-dimensional TEXAS code [6] can reasonably simulate the fuel-coolant mixing behavior, fragmentation, propagation and expansion. 2-dimensional JASMINE code [7], which is a stratified Monte Carlo technique, was first used to evaluate the containment failure probability by ex-vessel steam explosion. Monte-Carlo 3D Radiative Transfer Code (MC3D) [5] is a thermo-hydraulic multiphase flow code and can be used in modeling steam explosion.

SIMMER-III code is a 2-dimensional, multi-velocity-field, multiphase, multicomponent, Eulerian, fluid-dynamics computer code coupled with a space- and energy-dependent neutron kinetics model [8]. It was first developed to analyses core disruptive accidents in liquid-metal fast reactors (LMFRs), and was demonstrated its reasonable flexibility in some FCI simulations [9].

In this paper, the applicability of the SIMMER-III code in simulating the premixing phase of FCI process is verified in comparison with a related jet-type experiment in literature [4].

The models of SIMMER code

In the numerical simulation of FCI premixing phase, several physical fields should be considered simultaneously and accurately, which mainly include flow dynamics, melt fragmentation, heat transfer and boiling or vaporization. In this section, the related models of SIMMER-III code are simply introduced.

Fluid dynamic algorithm

In the fluid dynamic module, multicomponent and multi-velocity field are considered. The basic conservation equations including fluid mass, momentum and internal energy. The overall fluid-dynamics solution algorithm is based on a time-factorization approach [10].

Flow regime and interfacial area model

To calculate the mass, momentum, and energy transfer terms between fuel and coolant components, one should obtain contact interfaces for the transient state. In the SIMMER-III, bubbly, dispersed and in-between transition regimes are modeled for the mixture of gas and liquid phases in the pool flow without structures [9]. For the mixing of two liquid components, an interfacial area convection model is used as

$$\frac{\partial A_M}{\partial t} + \nabla\cdot(\mathbf{v}A_M) = S_M \tag{1}$$

where A_M, and S_M denote the interfacial area per unit volume and source term of component M, respectively.

Drag force model

To consider the interaction between different fluid phases, the drag force term in the momentum equation is calculated based on an analogy from engineering correlations of steady-state two-velocity flow, where

$$F_{drag} = \sum_{\xi'} K_{\xi\xi'}\left(\vec{u}_\xi - \vec{u}_{\xi'}\right) = \sum_{\xi'}\left(\alpha_{\xi\xi'} + \beta_{\xi\xi'}\left|\vec{u}_\xi - \vec{u}_{\xi'}\right|\right)\left(\vec{u}_\xi - \vec{u}_{\xi'}\right) \tag{2}$$

$K_{\xi\xi'}$ is the momentum exchange function between the components ξ and ξ', $\vec{u}$ is the velocity field. α and β are the model parameters which stand for the viscos and turbulent term, and are functions of flow regime, volume fraction, velocities, binary contact areas, and viscosities.

Heat and mass transfer model

In the FCI process, the heat transfer is a very complicate issue which involving the vaporization/condensation (V/C) and melting/freezing (M/F) paths. In the SIMMER code, a non-equilibrium heat-transfer model and an equilibrium model are applied to solve the heat and mass transfer. The non-equilibrium model is used to calculate the phase transition at the interface where the bulk temperature of component cannot be used as interface temperature, such as vaporization/condensation. The net energy transfer rate from the interface can be defined as

$$q^I_{A,B} = q_{A,B} + q_{B,A} = a_{A,B}h_{A,B}\left(T^I_{A,B} - T_A\right) + a_{A,B}h_{B,A}\left(T^I_{A,B} - T_B\right) \tag{3}$$

where q, h and T is the heat transfer rate, heat transfer coefficient and Temperature, respectively. Subscript A,B denotes from component A to component B, and superscript I indicates the interface.

After obtaining the $q^I_{A,B}$, the mass transfer rate can be calculated basing on separated physical paths.

Numerical simulations

In this section, the applicability of the SIMMER code in simulating FCI premixing phase is verified, in comparison with a related jet-type experiment in literature.

Experimental description

A series of so-called PREMIX experiments [4] was performed in FZK (Forschungszentrum Karlsruhe, Germany) for the support of the licensing procedure of future light water reactors (LWR). In the experiments, the mixing behavior was investigated of a hot alumina melt which was discharged into water pool. Thanks to the simple experimental setup and fast process, the