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NUMERICAL INVESTIGATION OF CORIUM COOLABILITY IN CORE CATCHER: SENSITIVITY TO MODELING PARAMETERS

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ABSTRACT

To avoid settling of molten materials directly on the vessel wall in severe accident sequences, using of a 'core catcher' device in the lower plenum of sodium fast reactor designs is considered. The device is to collect, retain and cool the debris, created when the corium falls down and accumulates in the core catcher, while interacting with surrounding coolant. This Fuel-Coolant Interaction (FCI) leads to an energetic heat and mass transfer process and may threaten vessel integrity. For simulation of severe accidents, including FCI, the SIMMER code is employed at KIT. SIMMER is an advanced tool for CDA analysis of liquid-metal fast reactors (LMFRs) and other GEN-IV systems. It is a multi-velocity-field, multiphase, multicomponent, Eulerian, fluid dynamics code coupled with a fuel-pin model and a space- and energy-dependent neutron kinetics model. However, the experience of SIMMER application to simulation of corium relocation and related FCI is limited. To verify the code applicability to FCI in a large system, an in-vessel model based on European Sodium Fast Reactor (ESFR) was established and calculated by the SIMMER code. In addition, a sensitivity analysis on some modeling parameters is also conducted to examine their impacts. The characteristics of the debris in the core catcher region, such as debris mass and composition are compared. Besides that, the pressure history in this region, the mass of boiling sodium vapor and average temperature of liquid sodium, which can be treated as FCI quantitative parameters, are also discussed. It is expected that the present study can provide some numerical experience of the SIMMER code in plant-scale corium relocation and related FCI simulation.

1. INTRODUCTION

After a severe accident, the nuclear reactor core can be significantly damaged. To avoid contact of molten materials directly with the vessel wall, a 'core catcher' device is in the lower plenum of sodium fast reactors. The device is to collect, retain and cool the debris and is treated as a means of accident mitigation.

When the corium falls down and accumulates in the core catcher, it interacts with surrounding coolant, leading to Fuel Coolant Interaction (FCI). It yields an energetic heat and mass transfer process and may threaten vessel integrity. The FCI modeling is a very important part in the safety analysis and has been studied for a long time. Regarding the FCI simulation, some computational codes were developed with various levels of complexity. For instance, 1D TEXAS code (1) can reasonably simulate the fuel-coolant mixing behavior, fragmentation, propagation and expansion. 2D JASMINE code (2), 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) (3) is a thermo-hydraulic multiphase flow code and can be used in modeling steam explosion.

At KIT we apply the SIMMER code (4) as an advanced tool for CDA analysis of liquid-metal fast reactors (LMFRs). It is a multi-velocity-field, multiphase, multicomponent, Eulerian, fluid dynamics code coupled with a fuel-pin model and a space- and energy-dependent neutron kinetics model. Until now, the code has been successfully applied in numerical simulations for reproducing key thermal-hydraulic phenomena involved in CDAs (5) as well as performing some validations of FCI experiments (6).

However, there is still a limited set of publications on SIMMER simulation of corium relocation and related FCI in the power plant scale. In the paper, to investigate the code applicability to large scale simulations, an in-vessel model based on European Sodium Fast Reactor (ESFR) (7, 8) is established and calculated by the SIMMER code. This model is based on an ESFR plant in the CP-ESFR project (Collaborative Project for a European Sodium Fast Reactor), which is to fulfil the criteria of the next generation reactors (Gen IV). It is a promising sodium-cooled fast reactor (SFR) type of 3600 MWth thermal power and 1500 MW electrical output in a commercial size. In a follow-up project, ESFR-SMART started recently, SIMMER will be applied for safety studies of a modified ESFR design to be established in 2018; the modified design with a lower coolant void effect, corium discharge tubes and other new features will be compared to the initial ESFR design. The paper contributes to these studies. In addition, a sensitivity analysis on some model parameters of the debris behaviors in the core catcher region and related FCI is also conducted to examine their impacts. The characteristics of the debris are compared, such as debris mass and composition. Besides that, the pressure history in this region, the mass of boiling sodium vapor and average temperature of liquid sodium, which can be treated as the FCI quantitative parameters, are also discussed.

2. SIMMER RELATED MODULES

2.1 FLUID DYNAMICS ALGORITHM

The fluid-dynamics algorithm is based on a time-factorization time-splitting approach. This is the four-step algorithm developed for the advanced fluid-dynamics model to solve the governing equations.

2.2 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.

2.3 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.

3. SIMULATION RESULTS

3.1 PLANT GEOMETRY AND ACCIDENT CONDITION

Typical ESFR geometry and core layout are shown in Fig. 1 and Fig. 2. There are several spare tubes to accommodate the core shutdown device (CSD) and diverse shutdown device (DSD). In the accident conditions, these tubes can discharge molten core materials toward the core catcher. Among that, seven tubes are in the center zone and more significant than those at the periphery of the core region according to the melting process. Therefore, the consequence of core melt discharging from these tubes in the center zone was considered in the calculation.

In the simulation, the discharging velocity of liquid fuel was explicitly set as boundary condition, and other core structure was totally neglected. The inlet value was according to the result in literature (9) due to its similarity. Fig. 3 shows the 2D simulation domain of the reactor vessel with cylindrical coordinate, which mainly includes core catcher region, cover gas region, heat exchanger and sodium pool. These tubes were approximated to locate in the center cell with identical cross section area. The computational time was set to 35.0 s with assuming all molten fuel was discharged into the lower plenum. The condition of the simulation case is summarized in Table 1. The sodium pool was assumed to be stagnant as the pump stopped.

3.2 MODEL PARAMETERS

The impacts of four model parameters in the SIMMER code related to the melting/freezing and vaporization/condensation processes were verified in the sensitivity analysis. The parameter list and applied values are shown in Table 2. The sensitivity case IDs were referred by the parameter names.

3.3 OVERALL BEHAVIOR

Material distribution snapshots in the selected cases are shown in Fig. 4, including the cases BC (a), DLF1 (b), DFP1 (c), FB (d), and HTC (e). The color bar indicates the material categories. One can see a similar FCI pattern from all figures in all cases. Gas or bubble areas form due to sodium vaporization and pressure wave during the quench process. Freezing fuel particles are mainly accumulated on the bottom edge of the core catcher. The characteristics effect of debris bed was not considered, such as particle shape.

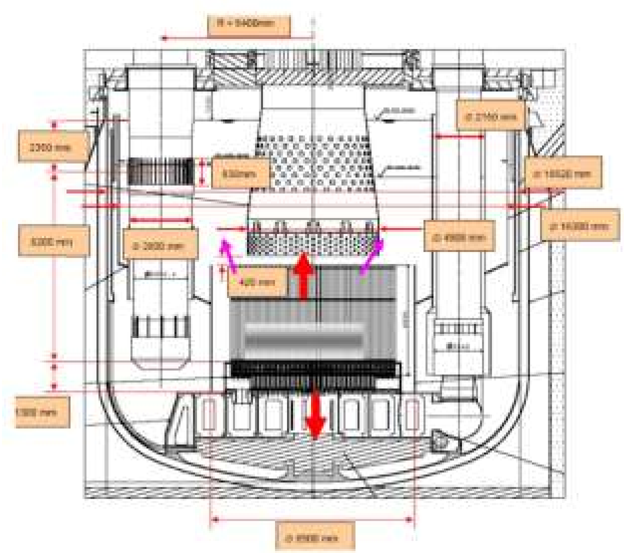


Fig. 1 ESFR Pool concept and potential relocation paths with geometrical values

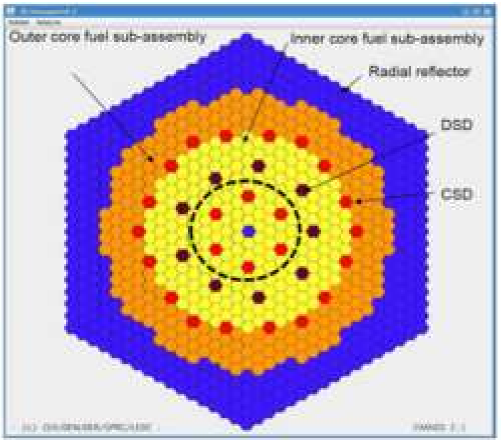


Fig. 2 Core layout of the ESFR reactor (7)

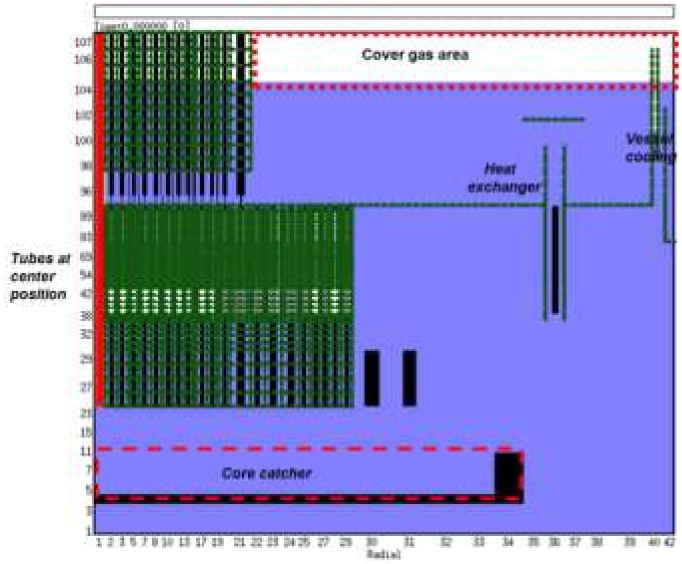
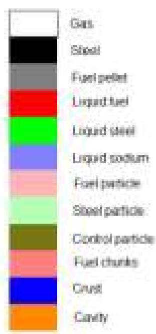
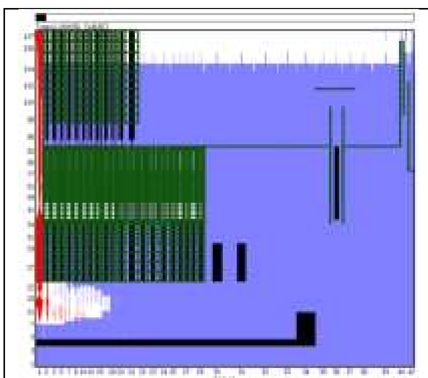
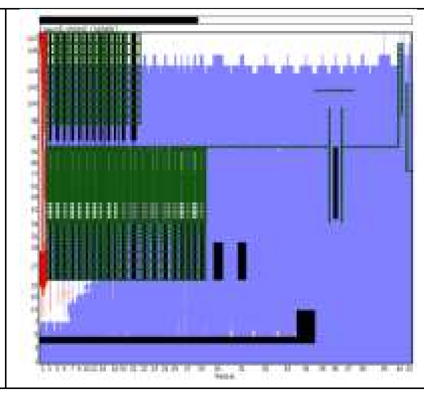
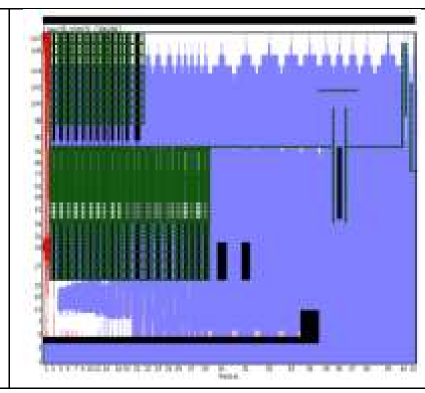
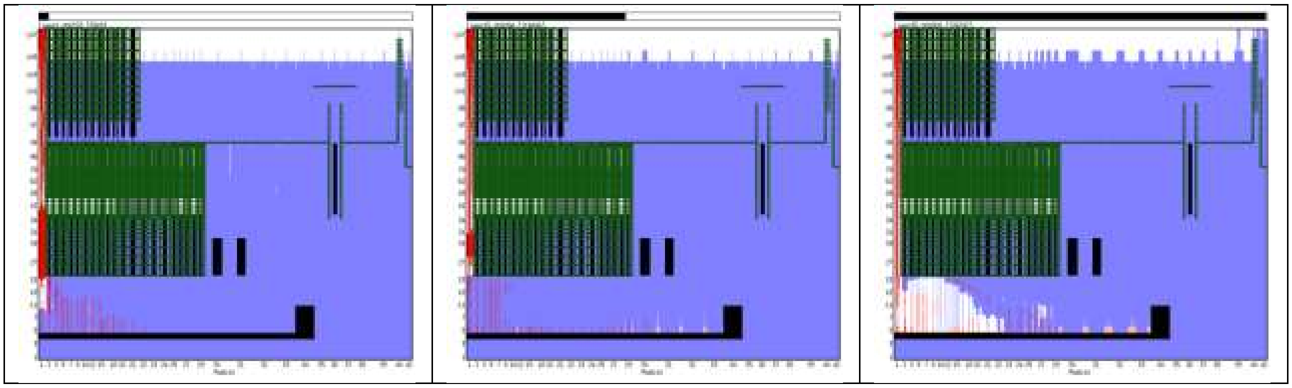


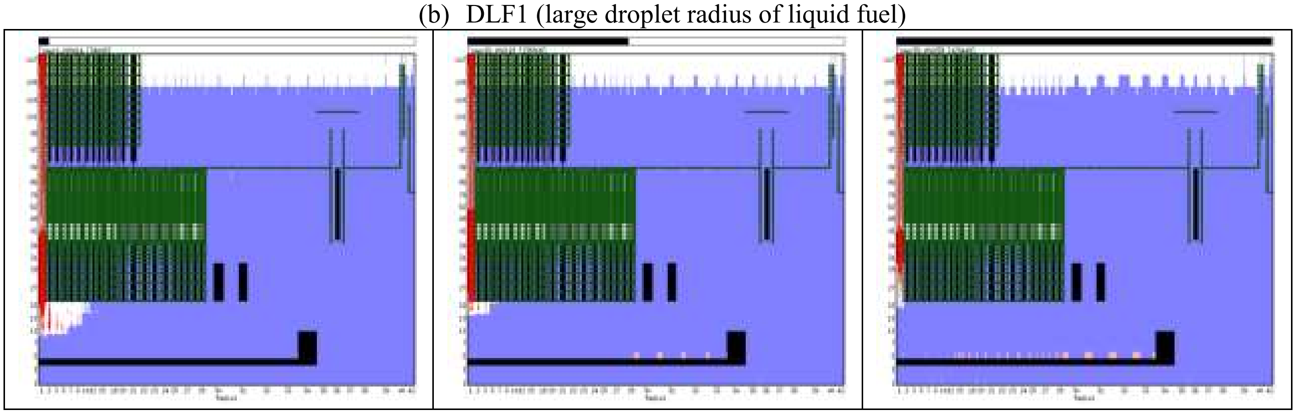
Fig. 3 simulation domain and initial position

1.0 s	15.0 s	35.0 s
		
		

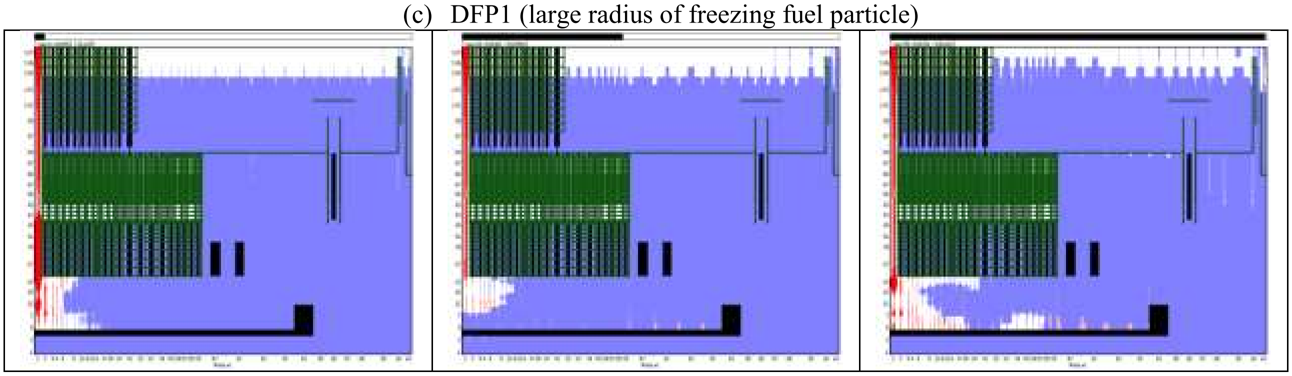
(a) BC (base case)



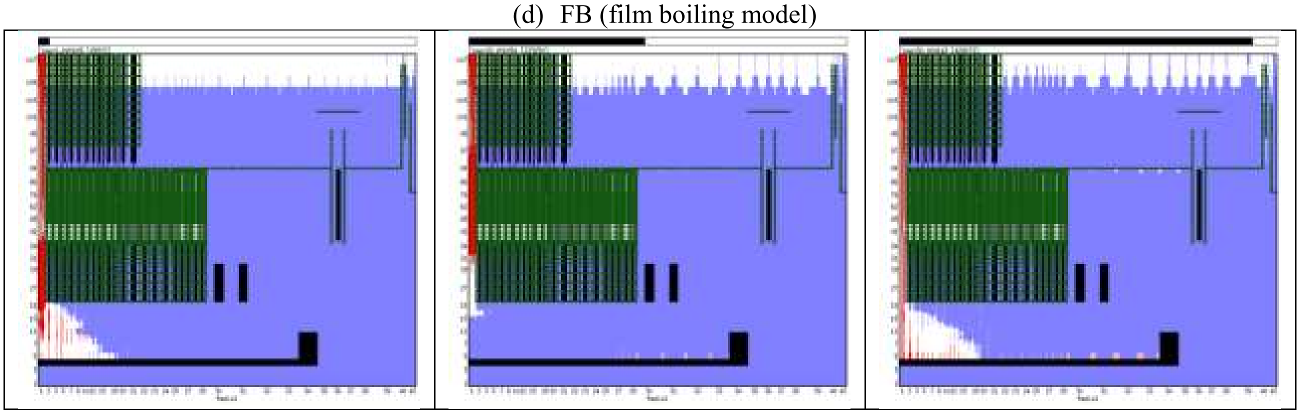
(b) DLF1 (large droplet radius of liquid fuel)



(c) DFP1 (large radius of freezing fuel particle)



(d) FB (film boiling model)



(e) HTC (Heat transfer coefficient ratio)

Fig 4 Material distribution snapshots in the selected cases

Table 1 Conditions of simulation case

Liquid fuel temperature (K)	3041.0
Total mass of discharged liquid fuel (kg)	$5.9*10^4$
Velocity of the corium (m/s)	4.13
Temperature of sodium pool in lower plenum (K)	673.0
Initial pressure of vessel (MPa)	0.1
Computational time (s)	35.0

Table 2 Model parameters in the base case and sensitivity analyses.

Parameter	Base case value (BC)	Sensitivity value	Case ID
d_{lf} : droplet radius of liquid fuel (m)	0.01-5.0*10-5	0.05 5.0*10-4	DLF1 DLF2
d_{fp} : radius of freezing fuel particle (m)	0.01-5.0*10-5	0.05 5.0*10-4	DFP1 DFP2
f_b : The film boiling model	Not considered	Considered	FB
$h_{lf,ls}$: Heat transfer coefficient ratio between liquid fuel and sodium	1.0	10.0	HTC

3.4 MASS OF FUEL PARTICLE AND COMPOSITION

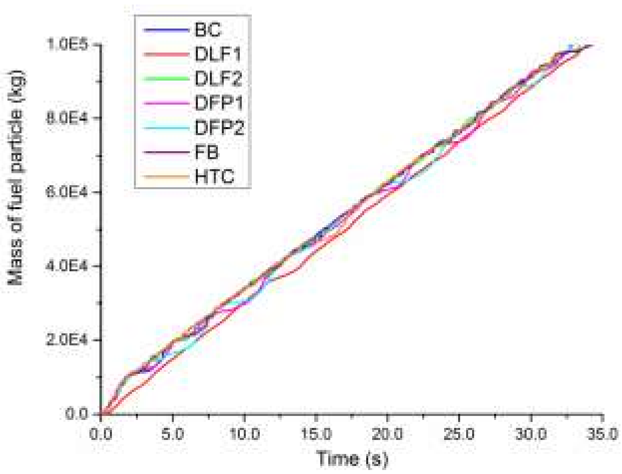


Fig 5 Mass of the fuel particle

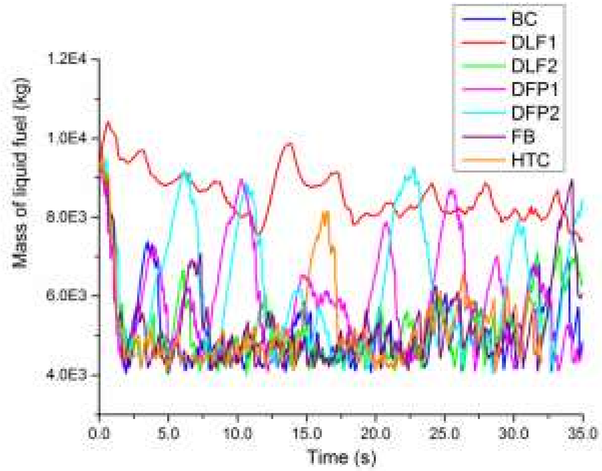


Fig 6 Mass of the liquid fuel

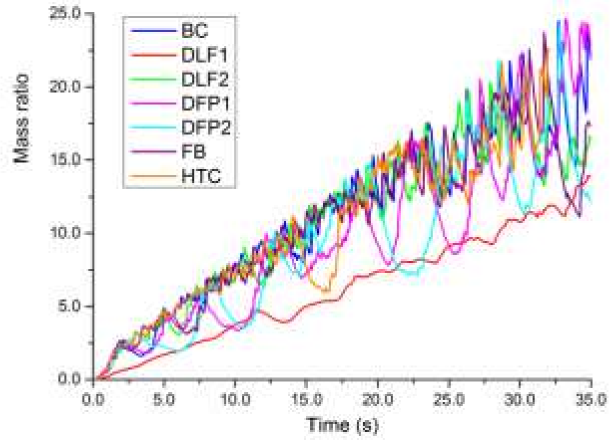


Fig 7 Mass ratio between fuel particle and liquid fuel

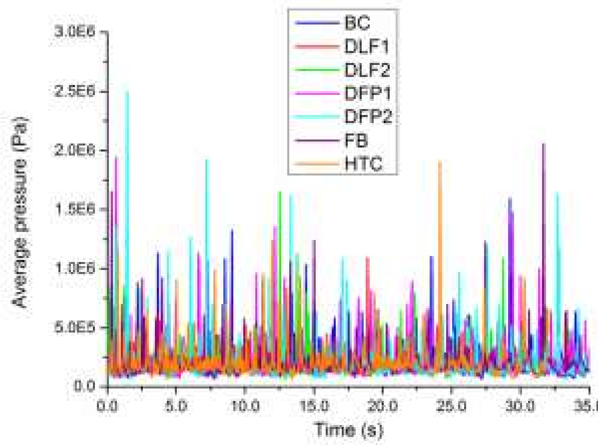


Fig 8 Average pressure

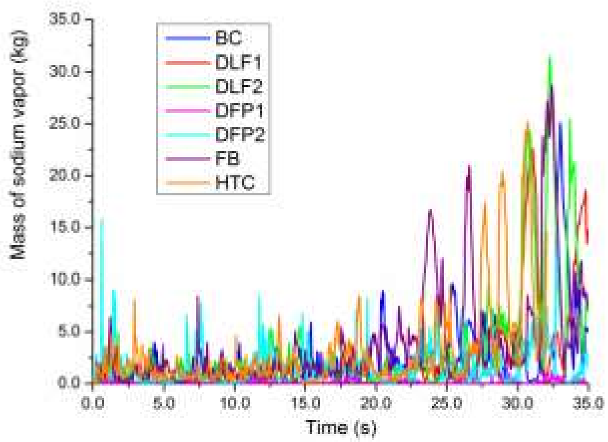


Fig 9 Mass of sodium vapor in the core catcher region

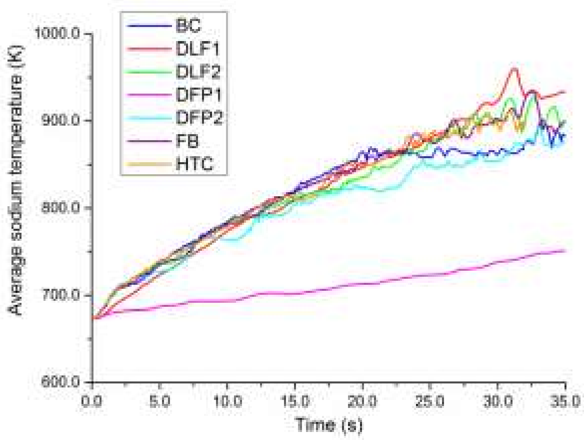


Fig 10 Average temperature of liquid sodium in the core catcher region

Fig 5, Fig 6 and Fig 7 show the total mass of the freezing particle and liquid fuel as well as their ratio in all simulation cases with identical boundary condition, respectively. The mass of freezing fuel particle shows almost linear increase, which indicates a quasi-steady state of heat transfer. As shown in Fig 7, the DLF1 case with large droplet size states largest variation in the mass ratio and implies slowest heat transfer.

3.5 PRESSURE HISTORY

Fig 8 compares the average pressure history in the core catcher region. One can see that pressure peak iteratively occurred during the process due to the FCI. In addition, the maximum peak value and pressure variation tendency are similar in all cases.

3.6 MASS OF BOILING SODIUM VAPOR AND TEMPERATURE OF LIQUID SODIUM

Fig 9 and Fig 10 show the mass of boiling sodium vapor and average temperature of the liquid sodium in the core catcher region. These parameters can represent the heat transfer rate, the degree of sodium vaporization and condensation. It can be seen that obvious different quantities only appear in DFP1 case, comparing to the other cases, which states that heat transfer to the liquid sodium is reduced significantly with large freezing particle size.

4 CONCLUSIONS

In this paper, an in-vessel model based on the ESFR was established and calculated by the SIMMER code. The corium coolability and related FCI in the core catcher region were investigated through the plant scale simulation. In addition, a sensitivity analysis on some model parameters was also conducted to examine their impacts.

The characteristics of the debris, such as debris mass and composition were compared. The results indicated slower freezing process occurred in the DLF1 case with large droplet size of the molten fuel and no obvious variation in the other cases. The average pressure history in this region showed a similar iterative peak and tendency in all cases. The mass of boiling sodium vapor and average temperature of liquid sodium, which can be treated as the FCI quantitative parameters, were also discussed. The figures show different quantities in DFP1 case, comparing to the other cases, which states a significant reduced heat transfer rate to liquid sodium with large freezing particle size. Therefore, the particle and droplet sizes show their more important impacts between all tested variables and should be carefully considered in the similar simulation.

These results gave a preliminary insight on the simulation of corium relocation and related FCI in large scale. It is expected that the present study can provide some numerical experience of the SIMMER code and can be used for the further FCI simulation in power plant-scale.

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