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Improvement of Model for SIMMER Code for SFR Corium Relocation Studies

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Abstract**—**The in-depth understanding of severe accident propagation in Generation IV of nuclear reactors is important so that appropriate risk management can be undertaken early in their design process. This paper is focused on model improvements in the SIMMER code in order to perform studies of severe accident mitigation of Sodium Fast Reactor. During the design process of the mitigation devices dedicated to extraction of molten fuel from the core region, the molten fuel propagation from the core up to the core catcher has to be studied. In this aim, analytical as well as the complex thermohydraulic simulations with SIMMER-III code are performed. The studies presented in this paper focus on physical phenomena and associated physical models that influence the corium relocation. Firstly, the molten pool heat exchange with surrounding structures is analyzed since it influences directly the instant of rupture of the dedicated tubes favoring the corium relocation for mitigation purpose. After the corium penetration into mitigation tubes, the fuel-coolant interactions result in formation of debris bed. Analyses of debris bed fluidization as well as sinking into a fluid are presented in this paper.

Keywords**—**Corium, mitigation tubes, SIMMER-III, sodium fast reactor (SFR).

I. INTRODUCTION

THE goals for Generation IV are defined within GIF (GenIV International Forum). The objectives concern the sustainability, economics, safety and reliability as well as proliferation resistance and physical protection. In terms of safety and reliability the current objectives of GenIV projects are to define reactor design in order to progress in reactor technology, at an industrial scale. Design improvement studies of Sodium Fast Reactors are ongoing in USA, Japan and France, in order to mitigate the accident as well as severe accident consequences, if they occur. Thanks to the large amount of R&D programs on fast breeder reactor safety in the last seventies and eighties, some complex mechanistic codes like SIMMER (later presented in this paper) enable to treat coupled thermohydraulic and neutronic aspects for all events of various fast reactor hypothetical accidents, even in three-dimensional geometries. The CEA decided to carry out such studies, by simulating the main physical phenomena occurring during unprotected core accident transients leading to core melting.

The studies presented in this paper are focused on the core region and related to the modeling of phenomena concerning relocation of corium out of this region during severe accident scenarios. These studies concern the secondary phase of accident, where the core is degraded and/or fuel is already melted. In order to mitigate, the dedicated tubes are placed in the core. Their function is to eliminate the uncontrolled corium motion and to avoid high energetic fuel coolant interactions. The modeling improvements performed in order to realize thermohydraulic calculations performed with SIMMER-III code are presented and discussed further on. The main thermohydraulic features are also compared with analytical results.

II. HEAT TRANSFER MODEL IN SIMMER-III CODE

The SIMMER-III has been developed by the Japan Atomic Energy Agency (JAEA). It is a two-dimensional, multi-velocity-field, multi-component, Eulerian fluid-dynamics code coupled with a fuel-pin model and a space-and energy-dependent neutron transport kinetics model. The partners of the SIMMER-III program (PNC, FZK and CEA) are conducting a systematic validation of the code. The assessment program consisted in two phases: Phase 1 for fundamental or separate-effect code assessment of individual models, and Phase 2 for integral code assessment for key physical phenomena relevant to fast reactor safety. The two phases have been completed and the code is used for reactor application [1].

The objective of SIMMER-III calculations presented in this paper is to simulate the molten fuel in the reactor core and its propagation during the secondary phase of the accident. Different validation studies covered partially our domain of calculations. The corium penetration into tubes was validated via experimental results GEYSER [2]. The fuel coolant interaction was compared with TERMOS [3] and THINA [4] results. The validation of SIMMER models with the first EAGLE tests focused on pool-to duct heat transfer and the crust formation [5].

For the mitigation scenario, the phenomena of molten pool heat exchange with surrounding structures are important. The intensity of heat transfer influences the instant of structure rupture that is important for further degraded material propagation. Thus, in this paper, we focus on the heat transfer modeling in SIMMER-III. The first completed validation of this domain was performed with SCARABEE BF2 experimental results [6]. An important number of calculations with SIMMER-III of the SCARABEE BF2 experiment were performed [6]. The purpose of these studies was to provide

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data about fuel boiling pools. On the overall, the calculation results were quite satisfying. However, the axial heat flux profile was identified to be too flat compared to experimental results. The discussion on heat transfer coefficients modeling of SIMMER-III, in the light of the application of the code to the SCARABEE boiling pool tests BF2, was already introduced in JAEA [7].

In our analyses we also identify the lack of heat transfer correlations applied for liquid-structure heat transfer. The bubbly flow region is our first domain of interest. This region is illustrated in Fig. 1.

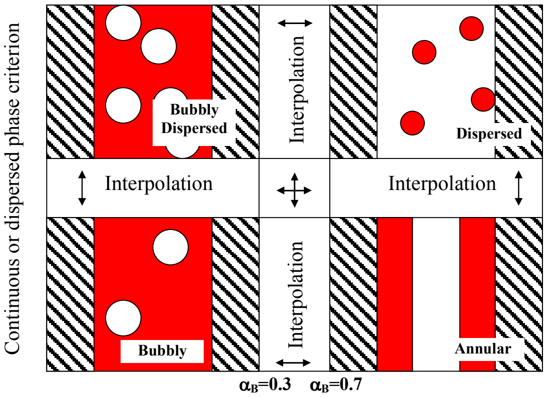


Fig. 1 Liquid-structure flow boiling map in SIMMER-III

In a bubbly flow region (see Fig. 1), the single-phase liquid-structure heat transfer coefficient for forced-convection is used. The asymptotic value of heat transfer coefficient at low velocities is a conduction term. Heat transfer coefficient *h [W/m²/K]* depends upon the pipe geometry in terms of a hydraulic diameter *Dh [m]* as follows:

$$\begin{aligned} h &= h_{COND} + h_{FC} \\ h_{FC} &= \frac{kNu_{Dh}}{Dh};\quad Nu_{Dh} = 0.023\,\mathrm{Re}_{Dh}^{0.8}\,\mathrm{Pr}^{0.3} \\ h_{COND} &= \frac{5k}{Dh} \end{aligned} \tag{1}$$

where k is the fluid thermal conductivity [W/m/K], *Re* is Reynolds number and *Pr* is Prandtl number. This heat transfer is appropriate for scenarios in which forced-convection liquid flow is important e.g. liquid fuel motion in tubes and ejection in quick transients. However, in a liquid fuel boiling pool in a degraded core surrounded by fuel assembly tube, the movement of the fluid is governed by thermal expansion. This represents a natural convection heat transfer, which is driven by liquid temperature and boiling-induced density differences as illustrated in Fig. 2.

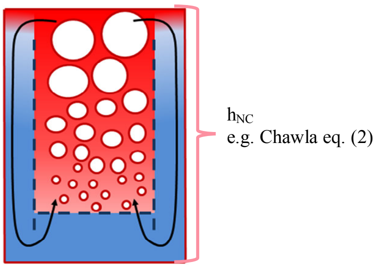


Fig. 2 Natural circulation flow in boiling pools

A natural convection heat transfer coefficient valid for these liquid fuel and metal pools was found in bibliography and can be described with Chawla correlation [7]:

$$\begin{aligned} h &= h_{NC} \\ h_{NC} &= \frac{k}{x}Nu_x = \frac{0.16\left[\left(\beta\Delta T_w + 3\alpha\right)\dfrac{gk^3}{\nu^2}\right]^{1/3}\mathrm{Pr}^{1/3}}{\left[1+\left(\dfrac{0.492}{\mathrm{Pr}}\right)^{9/16}\right]^{16/27}} \end{aligned} \tag{2}$$

where x is the depth from the pool surface [m], β liquid thermal expansion coefficient [1/K], ΔT_w temperature difference between the bulk fluid and structure [K], α void fraction of boiling pool, g gravitational acceleration [m/s²] and ν is kinematic viscosity [m²/s].

In this paper, the Chawla correlation in (2) is now implemented into SIMMER-III. The forced convection heat transfer in (1) is conserved as well but the criterion to distinguish between natural and forced convection flow based on flow velocity is introduced as recommended in [7]:

$$h_{NC} \Leftrightarrow V^{2.4} < 1000(\beta\Delta T_w + 3\alpha)Dh^{0.6} \tag{3}$$

Here, the V is the fluid axial velocity [m/s].

III. VALIDATION OF HEAT TRANSFER MODEL

In this paragraph we demonstrate the non-validity of correlation in (1) for the liquid fuel – structure heat transfer governed by natural circulation flow. Simple test geometry is simulated in SIMMER-III and the calculation results are compared with analytical results ongoing at CEA. These analytical models developed by CEA are based on bibliographic studies [8] of fuel molten pool heat transfers as is illustrated in Fig. 2.

Let us consider the molten pool geometry as shown in Fig. 3. The geometry characteristics and initial conditions of this test case are summarized in Table I. The objective is to simulate a molten pool with low power to avoid vaporization and pool sloshing. At the initial pressure 1bar, the saturation temperature of the liquid fuel is about 3650K. The initial fuel temperature is set to 3100K.

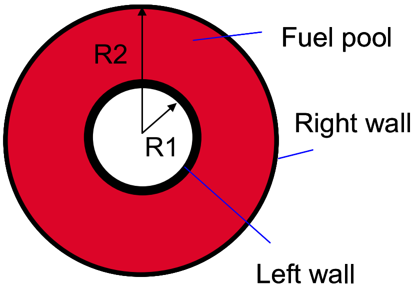


Fig. 3 Liquid fuel-structure simple case calculation

In this simple case calculation, the fuel crust thickness on the tube structure is initialized corresponding to steady state. Otherwise, the energy of solidification of the crust is a dominant heat transfer compared to convection heat transfer. If there are longer transient processes, the fuel crust has time to grow up on the tube surface. In this case the convection heat transfer becomes dominant. It is thus important for us to validate the convection heat transfer to predict correctly the thermal structure loading and instant of tube rupture. It can be seen in Fig. 4 that SIMMER new model in (2) predicts now correctly the convection heat transfer coefficient. The values are close to analytical results verified on experiments [8]. On the other hand, the previous SIMMER model in (1) underestimates the heat transfer. Moreover, we observed that the heat transfer coefficient expressed in (1) depends strongly in SIMMER on mesh width (see Fig. 5). This is due to the notion of hydraulic diameter that is taken locally and depends on mesh size.

TABLE I
TEST CASE GEOMETRY CHARACTERISTICS

Cylindrical geometry	
Radius R1 [mm]	91.88
Radius R2 [mm]	241.3
Left Tube thickness [mm]	11.7
Right Tube thickness [mm]	9.79
Liquid pool height [mm]	224
Initial & Boundary conditions	
Temperature fuel [K]	3100
Temperature tube [K]	1000
Power [MW]	0.23
Pressure [bar]	1

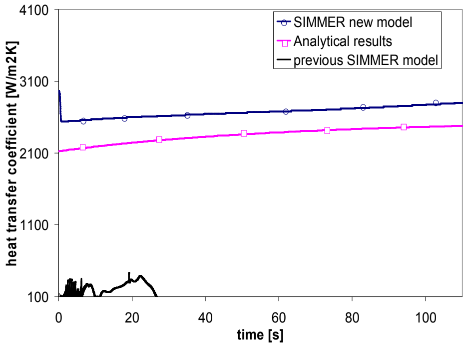


Fig. 4 Liquid-structure heat transfer coefficient for simple case test (one radial mesh nodalization)

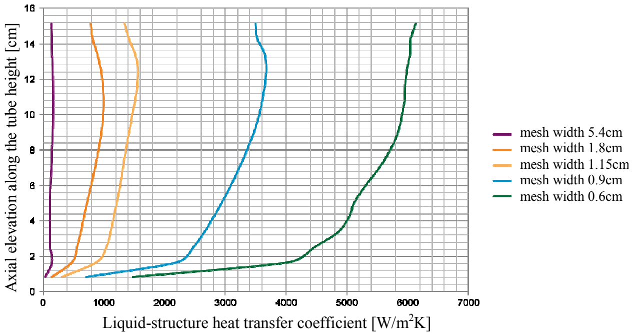


Fig. 5 Dependence of heat transfer coefficient (1) on mesh width, previous SIMMER-III model results

Our last remark on hydraulic diameter might lead reader to assume that the heat transfer coefficient in (1) can correctly predict the natural circulation heat transfer, if the hydraulic diameter follows the boundary layer thickness of heavier liquid along the cold crust (see Fig. 6). However, boundary layer thickness varies in direct proportion to pool depth and varies also through transient processes. Thus, it is difficult to initialize the mesh geometry in SIMMER that follows this boundary layer thickness during the whole calculations.

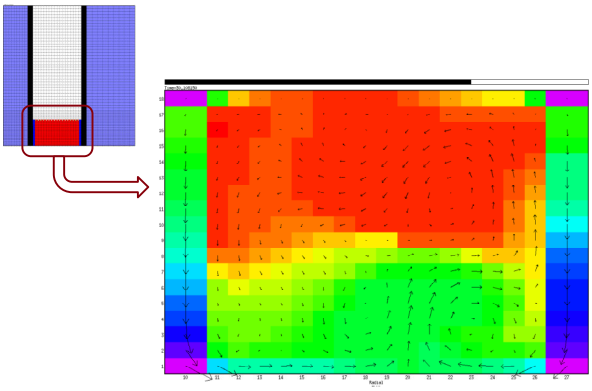


Fig. 6 Mesh scheme following the boundary layer thickness of the colder fluid returning in a heated pool

In conclusion, we demonstrated that the liquid-structure heat transfer model should be improved to simulate the natural circulation flow and thus to predict correctly the instant of structure thermal failure. It was demonstrated that for steady-states where the crust is already formed on the tube wall, the previous SIMMER-III models will predict much longer time of tube rupture because the heat transfer is small and based only on conduction. A proposed liquid-structure correlation for natural circulation flow in molten pools is introduced. Applying this new correlation, the heat transfer is independent on hydraulic diameter. Moreover, a criterion to distinguish between natural circulation and forced convection flow is introduced. This criterion is based on fluid velocity.

IV. LARGE SCALE CORIUM RELOCATION STUDIES

As we already mentioned, the main objective of SIMMER calculations summarized in this paper is to study the molten fuel movement in reactor core. The purpose is to focus on inherent safety features related to fuel expansion where:

- axial fuel expansion leads to a reduction in fuel density in the active core region, and thus has a negative reactivity effect;
- radial molten core propagation is typically one of the largest reactivity feedback components due to the sensitivity of fast reactor cores to geometry changes.

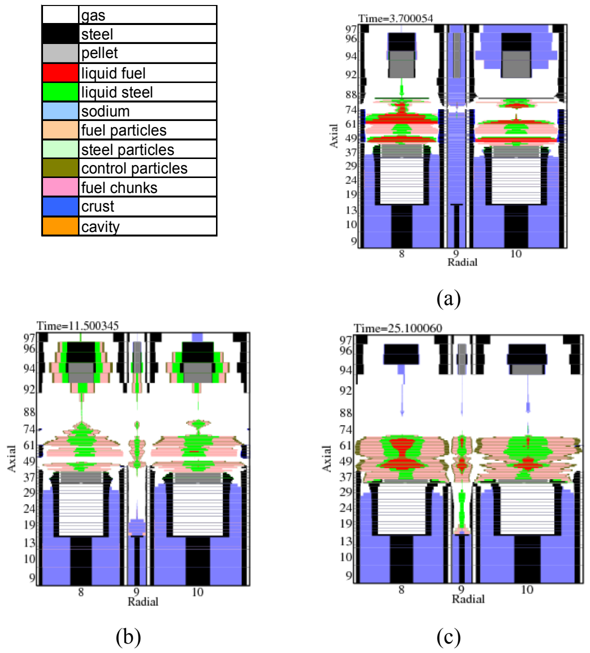
We recall here that in sodium fast reactor transients, only the unprotected accident scenarios may lead directly to core degradation and melting. Loss of DHR function would lead first to vessel failure. The control rods placed initially in the core region do not fell down and thus do not stop the neutron reaction i.e. no scram. Indeed, we focus on their possible mitigation function in the secondary phase of the accident. We also assume that other dedicated tubes are installed in the core to mitigate the accident. Firstly, if there is radial corium propagation, the fuel material will accumulate in these mitigation tubes. Secondly, if there is axial fuel relocation, the fuel will be transferred into upper and lower core regions with lower neutron heat flux and residual sodium. The objective is to evaluate these mitigation features in order to decrease the core reactivity and enhance the fuel sodium cooling.

A. Corium Propagation into Mitigation Tubes

The initial core state in our large scale calculations corresponds to reactor core, where the fuel is initially melted in each fuel assembly. The primary phase was less energetic and fuel material was not dispersed during this phase. The core is initially at nominal power and small variations of total power due to material movement are taken into account in calculations. In these calculations, no neutron reaction module is activated in SIMMER and power is an input parameter. The importance of heat transfer models was discussed in previous paragraph and the new model is directly applied within these calculations. Sensitivity studies of core initial temperatures, power and sodium flow are being performed. In this paragraph we focus on test case with zero sodium flow i.e. primary pump is set off at secondary phase of accident.

In the initial reactor core geometry, each mitigation tube is surrounded with six fuel assemblies. There is a lack of the SIMMER 2D modeling, where the core is modeled in axis-symmetric cylindrical nodalization. Thus, the number of fuel assemblies in direct contact with mitigation tubes is not correctly represented. The tube volumes, tube thickness as well as hydraulic diameters are conserved.

The SIMMER calculations indicate that the fuel assembly and mitigation tube surface is rapidly thermally attacked due to liquid-fuel structure heat transfer. At nominal power, the failure occurs within about 4s after thermal attack (see Fig. 7 (a)). Firstly, the axial fuel propagation towards the upper parts of mitigation tubes is observed. This is due to the fact that sodium is initially present in mitigation tubes and violent fuel coolant interactions (FCI) occurs. Fuel coolant interactions result in small fuel particle formation (<1mm) and local pressure increase up to 8-10bars. During this phase, the fuel particle fluidization is observed (see Fig. 7 (b)). We concluded that the fuel escape through the upper part of mitigation tube during FCI phase is possible and depends strongly on tube geometry i.e. upper tube restrictions, hydraulic diameter and exchange surface. Secondly, when the sodium in mitigation tube is vaporized, the fuel axial propagation towards the bottom core region occurs. An important amount of fuel is accumulated in the mitigation tubes (see Fig. 8) so we expect a reduction of core reactivity due to this fuel dispersion. Indeed, no further fuel propagation below the core region is observed if mitigation tubes are restricted at bottom (see Fig. 7 (c)). The lower hydraulic diameter at the bottom as well as system pressure in the lower plenum stops further fuel propagation. Moreover, the sodium present in the lower plenum has significant cooling capacity. The bottom core region is also a zone of no neutron heat flux. Finally, the fuel particle formation and accumulation in this region are observed.



(a)

(b) (c)

Fig. 7 SIMMER-III results on fuel and steel ejection into mitigation tube

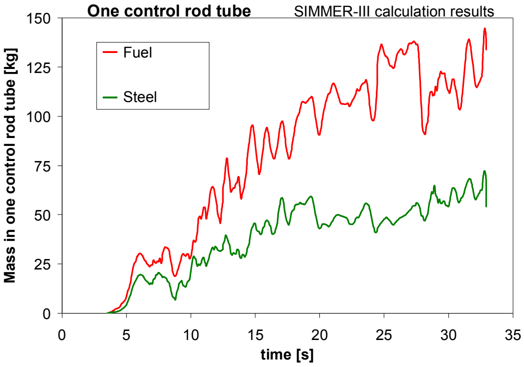


Fig. 8 SIMMER-III results on time evolution of fuel and steel ejection into one mitigation tube

B. Particulate Debris Bed Formation and Coolability

In SIMMER-III calculations we observed that for downward fuel motion, it is more likely that there will be blockage formations in the region below the core due to the much lower temperatures in that region, which would delay the axial fuel dispersal in that direction.

This phenomenon occurs in mitigation tubes in the core region discussed in previous paragraph. In these regions it might be explained due to lower diameter channels e.g. also at nominal state, sodium flow is ten times lower in these tubes than in fuel assemblies. At accident transients we also expect that the sodium-structure contact would continue within the spaces between the ducts in the bottom part of mitigation tubes.

Considering the difficult downward path for the melt and the low temperatures in the regions below the core, it will take relatively long time for the fuel to reach lower core regions. The melt will enter the sodium gradually, leading to complete fragmentation, but the degree of lateral spreading may be small. The melt will contain considerably more steel.

Indeed, the current mitigation scenarios at GenIV reactors assume that if the molten fuel/steel mixture in the core cannot be contained in a coolable configuration, it will relocate to the in-vessel core catcher. The role of the in-vessel core catcher is to ensure that the relocated core material does not come in direct contact with the reactor vessel, and is retained in a sub-critical, coolable configuration inside the reactor vessel.

It is assumed that complete fuel penetration into the in-vessel core catcher is highly likely if there is no bottom restriction in the mitigation tubes and they are connected with lower pressure plenum as well. These could provide an effective path for the fuel escape from the core. The preliminary calculations with SIMMER-III were performed to study these phenomena (see Fig. 9). Indeed, the test cases demonstrated that the particle accumulation in the lower part of the mitigation tubes occurs even if there is no bottom restriction. It is important to note the hydraulic diameter in these mitigation tubes is much larger compared to particle size i.e. D_h/d_p~160. Thus, we assume that the particle blockage in mitigation tubes is not possible to occur.

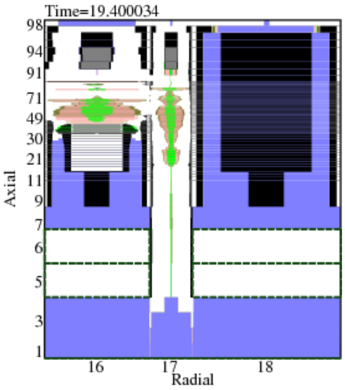


Fig. 9 Possible effective path for the fuel escape from the core, SIMMER-III calculations

For further calculations, we recommend to study the impact of particle size and particle-fluid effective viscosity coefficient on fuel propagation. Regarding into SIMMER models we observed that the current particle-fluid viscosity coefficient reaches high values for large particle volume fractions (see Fig. 10). This leads to particles accumulation, blockage and local pressure increase. Consequently, the pressure in the mesh increases and numeric problems in SIMMER calculations appear.

The first modifications on effective particle-fluid viscosity were already proposed after the validation on GEYSER [2]. However, all correlations on particle-fluid viscosity illustrated in Fig. 10 seem not to be established for case where particles are sinking into long tubes filled with sodium or gas. In our preliminary studies, the impact of effective viscosity on fuel axial propagation was tested. The preliminary results demonstrated that if there is constant effective particle-fluid viscosity coefficient (~1), the fuel axial bottom propagation increases but might be still limited due to very small particle size. Further investigations are ongoing.

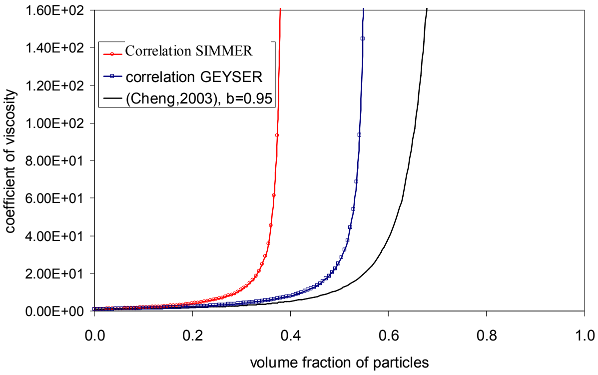


Fig. 10 Different particle-fluid effective viscosity multiplication coefficients

V. CONCLUSION

This paper dealt with model improvement in support to severe accident mitigation studies related to sodium fast reactors of Generation IV. These reactors are characterized by inherent safety features related to fuel heating and dispersion. Severe accidents with core melting are assumed only if an unprotected transient occurs. In this case, the control rod safety tubes do not fell down into the core and their mitigation function in a secondary phase of accident is studied. Also the dedicated tubes inside the core do not fail, so their mitigation function is studied as well.

In the first part of this paper, we discussed the validity of current liquid-structure heat transfer models implemented into SIMMER that is important to correctly predict the instant of action of mitigation devices. A simple case small scale calculation of liquid fuel initially formed in a fuel assembly tube has been simulated. The calculation results were compared with analytical results that are ongoing at CEA. It was demonstrated that the current liquid-structure heat transfer model in SIMMER-III code is valid for forced convection flow, where the notion of hydraulic diameter is important. It was concluded that when there is a refined representation of fuel assembly i.e. a refined radial meshing, the hydraulic diameter in SIMMER depends strongly on meshing and becomes arbitrary. For a natural circulation flow, the heat transfer coefficient in SIMMER for forced convection is no more valid. Eventually, this heat transfer coefficients in term of Dittus-Boelter correlation might be applied for natural circulation flow only if the representative length corresponds to the boundary layer thickness of heavier liquid flowing down along the cold crust. However, boundary layer thickness varies in direct proportion to pool depth and to the temperature difference driving the natural convection flow. Thus, the initialized mesh geometry in SIMMER cannot follow this boundary layer thickness during the whole calculations.

Secondly, reactor core calculations were performed with SIMMER-III applying the proposed model modifications. The studies focus on mitigation function of control rods when the fuel dispersion into this region occurs. The simulations of corium propagation from a postulated degraded core configuration have been presented. It was demonstrated that the fuel is ejected rapidly into mitigation tubes. Then it interacts with residual sodium in these tubes. This lead to violent fuel-sodium interaction, pressure increase and fuel cooling into a form of particles- debris bed. The fuel particle fluidization up to the upper core regions is possible and its axial ejection from the core depends strongly on design of upper restrictions of tubes.

The fuel axial propagation towards the lower core plenum is also possible but there should not be bottom restriction in mitigation tubes. These tubes should be connected with low pressure sodium plenum as well. Indeed, the first SIMMER-III calculations demonstrated that the fuel axial bottom propagation may be delayed due to the particle accumulation inside the mitigation tubes. However, due to the large hydraulic diameter we assume that the particle blockage in the large ducts is not physically possible. Thus, further investigations on model improvements and SIMMER-III calculations are ongoing.

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