Simulations of KROTOS Alumina and Corium Experiments: 
Applicability of the Improved Solidification Influence Modelling

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ABSTRACT

A steam explosion may result from the rapid and intense heat transfer that may follow the interaction between molten material and the coolant. The KROTOS alumina and corium experiments have revealed that the strength of the steam explosion depends on the melt composition. The experimentally observed differences are importantly attributed to the differences in the melt solidification and to the differences in the void production.

Due to the recognized importance of the solidification issue, an improved solidification influence model was developed and implemented into the development version of the MC3D code. The developed solidification influence model is based on an improved temperature profile modelling inside the melt droplet and the computation of the mechanical effect of the crust thickness on the fine fragmentation process. The purpose of the improved modelling is to improve the determination of the melt droplet mass, which can efficiently participate in the steam explosion.

In the paper the general applicability of the implemented improved solidification influence modelling approach is examined. The first objective was to identify those existing experiments, which are suitable for addressing the issue of solidification in the steam explosion process. The KROTOS alumina K44 and corium K53 explosion experiments were selected. The second objective was to perform comparative simulations of the relevant experiments. The results demonstrated the ability of the proposed solidification modelling approach to improve the simulation capabilities.

1 INTRODUCTION

A steam explosion may result from the rapid and intense heat transfer that may follow the interaction between the molten material and the coolant. In this energetic fuel-coolant interaction (FCI) process part of the melt energy is intensively transferred to the coolant during the melt droplets fine fragmentation process in a very short time scale. The fine fragmentation process rapidly increases the melt surface area, vaporizing more coolant and increasing the local vapour pressure.

KROTOS steam explosion experiments have revealed important differences in behaviour between simulant alumina and oxidic corium melts [1-3]. Especially the energy efficiency, defined as the ratio between the kinetic energy after the explosion and the initial thermal energy of the melt, was for the oxidic corium melt (0.02-0.15%) significantly lower than for the simulant alumina melt (0.87-2.48%). Differences in the material physical properties are one of the probable reasons for the observed differences in the steam explosion efficiency. The experimentally observed differences are importantly attributed to the differences in the melt jet break up, the melt solidification and the void production. The crust
formation is believed to be one of the most decisive consequences of the material properties regarding the limitation of the steam explosion strength. Namely, the crust inhibits the fine fragmentation process of the melt droplets during the steam explosion and if the crust is thick enough it completely prevents it. Consequently, the crust formation during the premixing phase in combination with the void production and the jet break up could explain the observed differences in the explosion efficiency between simulant alumina and oxidic corium melts.

Recently, due to the recognized importance of the solidification issue, new solidification influence models are being developed and implemented into FCI codes. An improved solidification influence modelling (ISIM) was integrated also into the MC3D code [4], which is being developed by IRSN, France, and is a reference FCI computer code in the EU SARNET (Severe Accident Research NETwork of Excellence) and OECD SERENA (Steam Explosion REsolution for Nuclear Applications) programmes [5,6].

The purpose of the paper is to assess the ISIM approach on steam explosion simulations. The comparison between the default and improved treatment of the solidification influence inside MC3D is firstly given. Secondly, the general applicability of the implemented ISIM approach in the MC3D code is examined. Therefore the KROTOS alumina K44 [1] and corium K53 [2] triggered steam explosion experiments were simulated. The simulation results of the two tests are critically compared and presented. The discussion focuses on the melt droplet solidification issue.

2 SOLIDIFICATION MODELLING IN MC3D CODE

MC3D is a multidimensional Eulerian code devoted to study multiphase and multi-constituent flows in the field of nuclear safety [7]. It is built with FCI calculations in mind. MC3D is a set of two FCI codes with a common solver, one for the premixing phase and one for the explosion phase. In general, the steam explosion simulation with MC3D is executed in two steps. In the first step, the distributions of the melt, water and vapour phases at steam explosion triggering are calculated with the premixing module. In the succeeding second step, the escalation and propagation of the steam explosion through the premixture are calculated with the explosion module, using premixing simulation results as initial conditions and applying a trigger. The MC3D code was extensively validated.

In the MC3D code, the default modelling of the melt droplets solidification influence is by the comparison of the droplet’s bulk temperature with the melt solidification temperature [5]. If the melt droplet bulk temperature is higher than the melting temperature the melt droplets are treated as liquid, allowing droplets fragmentation. In reality the temperature profile inside a melt droplet is not flat and consequently a solid crust can form on the droplet’s surface much earlier than the droplet bulk temperature decreases below the melt solidification temperature. The default solidification model of the MC3D code is obviously not capable of predicting the crust formation. Therefore the mass of melt droplets, which can efficiently participate in the steam explosion, could be importantly overestimated. Additionally, the simplicity of the used flat profile has also an important effect on the heat exchange, which is related to the melt droplet surface temperature, and is so directly influencing important FCI processes, as the solidification and the void generation.

On the other hand in the development version of MC3D the solidification influence modelling is related to the modelling of the temperature profile inside the melt droplet and to the computation of the mechanical effect of the crust thickness on the fine fragmentation process [4]. The modelling of the temperature profile is accomplished with the temperature profile approach, where prescribed temperature profiles in different droplet layers are assumed and the time development of the temperature profile is calculated in space and time.
In the temperature profile approach the heat transfer between different droplets is assumed to be insignificant compared to the local heat transfer from individual droplets. It is assumed that the droplet is cooled by radiation only from the surface of the droplet. Heat transfer within the droplet is governed by heat conduction. The material properties are assumed to be constant and non-eutectic compositions are treated as eutectic ones. The melt droplet is divided into the liquid part, where the temperature profile is above the melting temperature, and into the solid part, where the temperature profile is below the melting temperature. The liquid part is further divided into a central and a boundary layer. The droplet with an initial uniform temperature is cooled at the droplet’s surface. The temperature conditions are progressing from the surface inside the droplet and therefore it is assumed that a parabolic temperature profile develops in the boundary layer. Beyond the boundary layer, i.e. inside the central layer, the uniform initial temperature profile is still maintained. The temperature profile in the crust layer on the droplet surface is considered to be linear for partly solidified droplets. The fine fragmentation criterion is based on the modified Weber number [4]:

\[
We^* = \frac{\rho_v x_{ref} D^3}{\rho \delta^2 \left(1 - \mu^2 \right)}
\]  

(1)

which considers the crust stiffness as a stabilizing force acting to retain the crust under the presence of the hydrodynamic forces. The crust stiffness depends on the crust thickness \(\delta_c\), the Young’s modulus \(E\), the Poisson’s ratio \(\mu\) and the relative velocity between the droplet and the coolant \(v_{rel}\). The modified Weber number was validated on experimental data, from which the critical modified Weber number (i.e. \(We_{crit}^*\)) for fine fragmentation was estimated to be between 1 and 5. The critical modified Weber number is used to distinguish whether the hydrodynamic forces are sufficient for crust fragmentation. The application of the developed ISIM enables a physically-based determination of the melt droplet mass, which can be efficiently involved in the fine fragmentation during the steam explosion process. Additionally, with the temperature profile modelling also predicting of the void production can be improved. Namely, the heat transfer between the melt droplets and coolant is strongly related to the droplet surface temperature. ISIM is implemented into the development version of MC3D by solving the standard set of equations (i.e. balances equations, interfacial area transport equation) and two additional transport equations for conserved quantities [4]. The conserved quantities are based on the most important droplet features regarding FCI behaviour. First, the crust stiffness was considered as an important feature, because it enables the correct prediction of the amount of droplets participating in the fine fragmentation process during the explosion phase. Second, the heat flux from the droplet interior to the surface was considered as an important property, because it enables to improve the surface temperature determination and reflects the history of the droplet’s cooling.

3 APPLICATION TO KROTOS EXPERIMENTS

A purpose of the developed ISIM is to improve the prediction of the observed differences in the explosion efficiency between alumina and corium melts. Therefore the KROTOS alumina and corium explosion experiments are considered to be relevant for the assessment of the ISIM approach.

In this section the choice of the experiments used for simulations is firstly argued. Next, relevant experimental and simulation conditions are presented. Finally, simulation results are presented and discussed. In the first part the simulation results of the convergence analysis are provided. The purpose of the convergence analysis was to establish the right mesh size, where the mesh size had no influence on the simulation results anymore. This was necessary to justify the choice of the mesh size for sensitivity study simulations provided in the second part.
3.1 Selected explosion experiments

Among the performed explosion experiments in the KROTOS test facility, the integral experiments K44 and K53 were chosen to check if the ISIM approach will correctly predict a weaker explosion for K53 than for K44 due to material effects, despite the experimental conditions in K53 were favouring a strong corium explosion and in K44 a weak alumina explosion. These triggered experiments were performed in the corium and alumina test series, which were performed in parallel. The conditions of the K44 and K53 experiments are given in Table 1.

The alumina K44 experiment was already extensively simulated in the frame of the SERENA programme, where comparative calculations of explosion experiments performed in KROTOS, TROI and FARO facilities were performed with different FCI codes (e.g. MC3D, ESPROSE, IDEMO, TEXAS) [6]. The K44 test was performed to confirm that even though the alumina melt does not explode spontaneously when poured into water with low subcooling as in previously performed K41 test, the explosion can still be triggered by an external pressure pulse. Obviously the saturated conditions used in the alumina K44 test were chosen with the aim of reducing the steam explosion efficiency.

On the contrary high sub-cooling conditions were used in the corium K53 experiment to reduce the void fraction, thus increasing the steam explosion efficiency. High void in the premixture in general reduces the explosion strength due to water depletion and the compressibility of the voided regions. On the other hand the crust formation, which hinders the fine fragmentation during the explosion phase, is faster in highly sub-cooled water. Consequently the low strength of the steam explosion in K53 may be presumably importantly attributed to the process of melt solidification.

Table 1: Initial conditions and main results [1,2].

<table>
<thead>
<tr>
<th>property</th>
<th>K44</th>
<th>K53</th>
</tr>
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<tbody>
<tr>
<td>melt composition</td>
<td>Al₂O₃</td>
<td>UO₂ wt 80% - ZrO₂ wt 20%</td>
</tr>
<tr>
<td>mass</td>
<td>1.5 kg</td>
<td>3.1 kg</td>
</tr>
<tr>
<td>temperature</td>
<td>2673 K</td>
<td>3129 K</td>
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<tr>
<td>release diameter</td>
<td>30 mm</td>
<td>30 mm</td>
</tr>
<tr>
<td>free fall in gas</td>
<td>0.44 m</td>
<td>0.44 m</td>
</tr>
<tr>
<td>water</td>
<td></td>
<td></td>
</tr>
<tr>
<td>height</td>
<td>1.105 m</td>
<td>1.105 m</td>
</tr>
<tr>
<td>temperature</td>
<td>363 K</td>
<td>290 K</td>
</tr>
<tr>
<td>sub-cooling</td>
<td>10 K</td>
<td>122 K</td>
</tr>
<tr>
<td>vessel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>pressure</td>
<td>0.1 MPa</td>
<td>0.36 MPa</td>
</tr>
<tr>
<td>temperature</td>
<td>328 K</td>
<td>295 K</td>
</tr>
<tr>
<td>gas</td>
<td>He</td>
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</tr>
<tr>
<td>results</td>
<td></td>
<td></td>
</tr>
<tr>
<td>global void fraction at triggering</td>
<td>10.4 %</td>
<td>3 %</td>
</tr>
<tr>
<td>maximum pressure</td>
<td>68 MPa</td>
<td>35 MPa</td>
</tr>
<tr>
<td>efficiency</td>
<td>2.48 %</td>
<td>0.05 %</td>
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</table>

3.2 Description of selected experiments

The KROTOS facility consists of the radiation furnace on the top, the release tube and the pressure vessel with the test section [1,2]. The pressure vessel together with the test section of the facility is schematically presented in Figure 1. The melt was prepared in the tungsten crucible, which was placed inside the furnace vessel. The cylindrical tungsten heater was used to melt corium and alumina. The crucible was then released into the release tube. A puncher stopped the falling crucible and broke the bottom of the crucible allowing melt release. The melt was released through a funnel at level 1.545 m, which defined the jet diameter of 0.03 m entering into the pressure vessel. The pressure vessel comprises the test section and the instrumentation for the measurement of the temperature, the pressure and the
Figure 1: KROTOS test section and pressure vessel [1] (left) with the geometry of the computational model consisting of 20x84 cells (right).

In both experiments a spontaneous steam explosion did not occur, but an external trigger was activated. The external trigger was able to destabilize the meta-stable state of the mixture, what resulted in the development of a steam explosion. The initial conditions and the main results are given in Table 1.

3.3 Simulation conditions

The KROTOS experiments were simulated and analysed with the development version of the MC3D code [4], which represents an extension of the original MC3D version 3.6.1 (see Section 2) [7]. Two parallel simulations were performed to demonstrate the applicability of ISIM and its influence on the calculation results. The simulations of both experiments were performed with the improved (i.e. ISIM) and with the default solidification model (i.e. DSIM). MC3D default or recommended numerical and model parameters values were reasonably used.

The experiments were modelled in a simplified axial symmetrical cylindrical 2D geometry (Figure 1). The radius of the mesh was 0.21 m and its height was 1.68 m.

The release location in the premixing phase was set to the level near the funnel’s exit at 1.54 m. The diameter of the release was 0.03 m and the initial melt velocity was set to $v_{jet}=1.5$ m/s. The initial velocity was estimated from the alumina K41 experiment, which was performed in the same test series as K44 [1]. The melt pour was presented as a jet continuous field. The fragmentation of the jet continuous field into the droplet field during the premixing phase was modelled with the global model [5]. The applied constant jet fragmentation rate in the global model was deduced from the comparison to a standard case, where for the standard case typical conditions in FARO experiments were chosen. The user parameter in the jet fragmentation rate calculation was defined for K53 simulations so that a similar jet break up length as observed in different KROTOS corium experiments was obtained [2]. No information regarding the break up length was given for alumina experiments. Therefore the break up length was estimated from the Saito correlation, which is a global correlation, where the break up length depends on the coolant and melt density, the melt impact velocity, the gravity and the diameter of the jet [5]. In the Saito correlation the only difference between K44 and K53 was assumed to be due to the densities. The estimated break up length was then used to define the user parameter in the jet fragmentation rate calculations for the K44
simulation. The size of the droplets created by the jet break up was based on the particle size distribution obtained from the analysed debris of the KROTOS alumina and corium premixing experiments. The droplets size was set to $D=15$ mm for K44 and $D=2$ mm for K53 [1-3]. The same size of alumina droplets was used also in the frame of the SERENA programme calculations [6]. Secondary break up of the melt droplets was not modelled, therefore the generated droplet size during the jet break up is also the final size of the droplets. The creation of the non-condensable hydrogen during the interaction of corium with water vapour was also not modelled. The experimental data about the fraction of non-condensable gases was not available anyway. Non-condensable gases in general reduce the strength of the steam explosion because they increase the premixture void fraction and hinder the direct melt water contact.

The premixing phase was simulated for a period of 1.5 s for K44 and 1 s for K53. The explosion phase was simulated for a period of 10 ms. In the K44 test and the K44 simulation the trigger was activated when the melt front penetrated till around 150 mm (i.e. $t_{150mm}$) above the bottom of the test vessel. In the K53 test and the K53 simulation the trigger was activated at melt bottom contact (i.e. $t_{MBC}$) [2]. The steam explosion trigger device in both experiments was the gas chamber of $15$ cm$^3$ charged to a pressure of 15 MPa and attached at the bottom of the test section. Therefore the trigger was modelled in the bottom-central cells of the test section (1.5 cm x 2 cm). The trigger consisted of a pressurized gas volume at 15 MPa.

Although alumina and corium properties needed for simulations with the standard MC3D version are available, the data are not sufficient to assess the modified Weber number in the development version. To calculate the modified Weber number with Eq. (1) the effective Young’s module and Poisson’s ratio are needed. The effective Young’s module is obtained by approximating the complex stress-strain behaviour of the material with a linear elastic behaviour up to the brittle break. The material properties for UO$_2$ were used because no appropriate data was available for the corium melt. The Young’s modulus of solid UO$_2$ at 2500 K is around 90 GPa [4] and for alumina at room temperature it is around 70 GPa [8]. UO$_2$ was estimated to behave in a linear elastic manner until a strain of 0.1% and after that ideally plastic up to the maximum strain of 3%. Therefore the effective Young’s modulus of 3 GPa was obtained. The effective Young’s modulus of 1.5 GPa for alumina was estimated from the ultimate strength of around 45 MPa at an estimated maximal strain of 3%. Poisson’s ratios 0.3 and 0.35 were used for corium and alumina, respectively.

3.4 Convergence analysis

The convergence analysis was performed by varying the mesh sizes. The number of cells in radial and axial direction was varied from 5 to 40 and from 21 to 168, respectively. A progressive grid was used in the radial direction whereas a regular grid was used in axial direction. The typical cell dimension inside the test section in the radial direction was varied from 4 mm to 50 mm. The cell dimension in the axial direction was constant and set to 10, 20, 40 or 80 mm.

The ISIM premixing simulation results for K53 are shown in Figure 2. The results show a small influence of the mesh size on the main global premixing simulation results unless the most coarse mesh sizes are used. On Figure 3 the main ISIM results (i.e. crust thickness, surface temperature) for K53 are compared for all simulated mesh sizes. The resolution of the results is improving with increasing mesh density.
Figure 2: Convergence analysis results of the most important parameters for ISIM premixing simulations of the K53 experiment.

Figure 3: Snapshot of K53 ISIM convergence analysis premixing simulation at time 0.6s. On the top side the bulk temperature (line) and crust thickness (field) are shown. On the bottom the surface temperature (field) is shown. The dashed line is used to mark the area where ISIM is used. Mesh sizes are 10x42 (left), 20x84 (middle) and 40x168 (right) cells.
3.5 Sensitivity study

The strength of the steam explosion depends on the mass of melt droplets, which can efficiently participate in the steam explosion – that is the mass of droplets capable of undergoing fine fragmentation in regions with enough water available for vaporization and for enabling the fine fragmentation process (i.e. available mass). The purpose of the sensitivity study was to vary those parameters which are uncertain and could have an influence on the available mass (e.g. experimental uncertainties, unknown material properties).

For the premixing simulations the results are given for variations of the jet inflow velocity and the size of melt droplets issued during jet fragmentation. Additionally, for the explosion simulations the results are given for variations of the critical modified Weber number and the triggering time. An overview of the performed sensitivity studies is given in Table 2. For the simulations the mesh size of 20x84 cells (Figure 1) was chosen (see Section 3.4). The typical cell dimension in the test section was 7x20 mm.

<table>
<thead>
<tr>
<th>Designator</th>
<th>Premixing</th>
<th>Explosion</th>
<th>Trigger</th>
</tr>
</thead>
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<tr>
<td></td>
<td>$v_{jet}$ [m/s]</td>
<td>$D$ [mm]</td>
<td>$W_{c_{crit}}^{*}$</td>
</tr>
<tr>
<td>N/A</td>
<td>1.5</td>
<td>15</td>
<td>2.0</td>
</tr>
<tr>
<td>N/A</td>
<td>1.5</td>
<td>15</td>
<td>2.0</td>
</tr>
<tr>
<td>N/A</td>
<td>1.5</td>
<td>15</td>
<td>2.0</td>
</tr>
<tr>
<td>D+</td>
<td>1.5</td>
<td>17</td>
<td>2.5</td>
</tr>
<tr>
<td>D-</td>
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<td>13</td>
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<tr>
<td>v+</td>
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<tr>
<td>v-</td>
<td>1.3</td>
<td>15</td>
<td>2.0</td>
</tr>
</tbody>
</table>

3.5.1 Premixing results

Due to uncertainties in the jet inflow the initial velocity of the jet was firstly varied in the premixing study. The release time was adjusted so that the released mass remained the same. As seen in Figure 4, the purpose was not to influence the total mass of the melt in water at triggering time, but to vary the total available mass. The explosion was triggered at ~1 s and at ~0.7 s for K44 and K53, respectively. At the triggering time all of the melt was released through the funnel and was already totally relocated into the test section. With a longer jet inflow time the average time for the droplet’s quenching was shorter and consequently the available mass could be larger. This can be observed in the K53 results once the melt was completely relocated into water. In the K44 results the variation of the inflow had a smaller influence since the droplets are large enough to remain liquid at the time of steam explosion.

Next, due to uncertainties in the jet fragmentation the effect of the droplet’s size was also analysed in the premixing study. The influence of the droplet size is very complex. It has an impact on both, the solidification and the void production. With larger droplets a longer time is needed to achieve the same crust thickness. As seen in Figure 4 this can be in general observed from K53 results where in the premixture the mass of droplets with a lower crust thickness is larger when the droplets are larger. Also the total area available for heat transfer between the droplets and the coolant decreases with increasing the droplet’s size. The decreased heat transfer area could then result in a decrease of the void production. As seen in the result the global void fraction was in general larger when the droplets were smaller. A
stronger effect of the droplet’s size is observed in K53 than in K44. The global void fraction at triggering time was around 12 % (K44) and 5 % (K53). The calculated global void overestimated the experimental values (Table 1).
Generally the results after melt bottom contact in Figure 4 show a significant decrease of the available mass. The decrease in K44 simulations is due to the coalescence of the liquid mass on the bottom of the test section, whereas in the K53 simulations the decrease is due to the strong effect of solidification and the increased void fraction on the bottom of the test section.

3.5.2 Explosion results

In Figure 5 and Figure 6 the calculated pressure loads at pressure transducer locations inside the test section (see Figure 1) are given for the performed explosion phase simulations (see Table 2). The experimental data are provided only for illustration, because the main purpose of the presented analysis is to demonstrate ISIM applicability and its effect on the results. The time axis denotes the time after explosion triggering. In the calculation of the pressure impulses, the initial test section pressure was subtracted from the calculated absolute pressure because the pressure loads are caused by the pressure difference.

Generally the K53 ISIM simulation predicted a significant reduction of the pressure loads if compared with DSIM results. For ISIM calculations the available mass was significantly lower and consequently the loads were lower (Figure 4 and Figure 6). On the other hand the K44 simulations do not show any important difference between ISIM and DSIM simulations, since at triggering time the crust has not started to grow yet (Figure 4 and Figure 5). With the used standard and proposed values of the MC3D model parameters, MC3D was able to reproduce globally the strong event observed in the K44 experiment. The accordance was expected because the standard and proposed values were obtained based on the KROTONS alumina tests simulation used to validate the models of the MC3D code [5].

A strong impact of the droplet size on the K53 results was observed (Figure 6). Larger loads were observed when the droplets were larger. Larger loads were expected since in smaller droplets the crust is progressing faster and since in larger droplets a thicker crust is needed to achieve the same fine fragmentation inhibiting effect than on smaller droplets. Additionally a delay in the development of the steam explosion is observed for smaller droplets due to the stronger inhibiting effect of the crust thickness.

Experimentally the position of the melt at triggering time was estimated from thermocouple measurements (i.e. TC in Figure 1). Due to uncertainties in the jet position at the trigger time, the start of the explosion simulation was also varied. By varying the triggering time the droplet quenching and consequently crust thickness was affected. Therefore the later the triggering was activated, the less was the available mass and the lower were the loads.

A sensitivity analysis of the implemented ISIM approach was performed also on the chosen critical modified Weber number. The fragmentation criterion affects the crust thicknesses, which can prevent the fine fragmentation process. By varying the critical modified Weber number the uncertainties due to unknown material properties were studied. By increasing the limit the available mass is decreased resulting in lower loads.

3.6 Discussion

The purpose of this section is to assess the ability of the developed ISIM approach to improve the determination of the available mass, which may efficiently participate in the steam explosion process. The influence of solidification in alumina experiments was minor mainly due to larger droplets sizes, which are issued at jet fragmentation. On the other hand the simulation results clearly indicate the necessity for the inclusion of the improved solidification modelling when the corium melt is used. Namely, the physically-based ISIM
approach enables to identify the part of the corium droplets, which cannot participate in the steam explosion, which is one of the most important results for reactor simulations. However the scatter of the K53 results reveals a lack of understanding of some phenomena such as the jet fragmentation and fine fragmentation.

The uncertainty of the premixing simulation results is mainly due to the uncertainties in the modelling of the jet fragmentation. During this process the melt droplets of different sizes are generated at different fragmentation rates. But in the simulations a constant fragmentation rate and droplets size was used with the global model. A step forward is therefore considered to be the use of a fully local model, which has been also implemented into the MC3D code. The fully local model considers the local velocities based on the Kelvin-Helmholtz instability model. The rate of the jet fragmentation is defined with the instability growth rate. The size of the issued melt droplets is related to the wavelength of the instability. Nevertheless the use of the fully local model is still considered to be quite unstable and difficult to handle [7], therefore its use was avoided in the frame of this work. Once the code will be capable to model the creation of different droplets sizes the implementation of several droplet’s field groups will be needed. At the moment the code uses only one droplet group. The introduction of several groups would enable the tracking of droplets with different sizes. This would improve the determination of the heat transfer between droplets and coolant and the
performance of the implemented ISIM. Consequently uncertainties in the premixing calculations would be reduced.

The uncertainties of the explosion calculations are related to uncertainties in the premixing calculations and uncertainties in the fine fragmentation process. The melt droplets are considered to undergo hydrodynamic fine fragmentation once the fine fragmentation criterion is satisfied. In that case fine fragments are being created with an established fine fragmentation rate. A modified Weber number was introduced as a fine fragmentation criterion for partly solidified droplets. This introduction enabled to improve the prediction of the available mass on a physical basis. Nevertheless the analysis has shown that the uncertainties in the implemented criterion have an important influence on the result. The uncertainties could be reduced by an improved knowledge of material properties and with additional experimental data for relevant crust thicknesses. Additional uncertainties are also due to the lack of knowledge about the fine fragmentation rate and the size of partly solidified melt droplets. At the moment the same fine fragmentation rate and fragments size as for liquid droplets is conservatively used. For a more accurate determination of these model parameters a more specific experimental investigation would be needed.

4 CONCLUSIONS

The experimentally observed differences in the steam explosion efficiency between corium and alumina materials are importantly attributed to the melt solidification and void production. Because solidification is recognized as a significant limiting phenomenon for the development of strong steam explosions, more accurate solidification influence models are being developed and implemented into FCI codes. The purpose of the presented work was to assess the applicability of the developed improved solidification influence modelling (ISIM) integrated into the exploring version of MC3D.

Simulations of the integral KROTOS alumina K44 and corium K53 experiments were performed. The purpose was to analyse how ISIM influences the mass of melt droplets, which can efficiently participate in the fine fragmentation process during the explosion phase. First the convergence analysis was performed to define an appropriate geometrical model used for sensitivity studies. After that sensitivity studies were performed. The sensitivity studies have shown only a minor dependence of the K44 results on the performed variations (i.e. jet inflow, melt droplet’s size, fine fragmentation size, triggering time), especially since the melt droplets are large enough to delay significantly the solidification. On the other hand the variations of the model parameters and the approach in the solidification modelling have an important influence in K53 simulations. The simulations demonstrated the importance of ISIM for corium experiments, where the droplets are smaller and consequently solidification has an important role on the strength of steam explosion. Additionally, the results have highlighted the importance of the jet fragmentation process during which the melt droplets are created and the fine fragmentation process during which the melt droplets are fine fragmented.

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