Potential of Vapour Explosion in Sodium

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ABSTRACT

One of the important safety issues during a severe accident in an innovative sodium cooled fast reactor is the likelihood and the consequences of a vapour explosion. In the paper a comparative analysis of the melt-sodium and melt-water mixing is used to analyse the vapour explosion potential for sodium. Additionally, the sensitivity study on the mixing of the melt with sodium is presented and discussed. The relevance of the jet inflow conditions, the melt initial temperature, and the coolant sub-cooling on the premixing conditions are highlighted. The results indicate that the potential of vapour explosion is lower in sodium than in water.

1 INTRODUCTION

In the frame of safety studies for the innovative sodium cooled fast reactors, the risk for the environment in a severe accident must be estimated. A vapour explosion can occur during the core melt accident when the rapid and intense heat transfer follows the interaction between the molten material and the coolant [1]. 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. Potentially severe dynamic loadings on surrounding structures, systems and components could be induced.

Several experimental programs were launched to help understanding and characterizing the vapour explosion phenomenon during the melt-sodium interaction [2,3]. Generally, no energetic events were observed in the experiments, where the sodium sub-cooling was of the order of some hundreds of kelvin. The absence of energetic events could be mainly attributed to the strong effect of the melt solidification preventing the fine fragmentation. But some experiments indicated that a vapour explosion could occur if the melt heats up the sodium in the mixing zone close to the saturation temperature. In those conditions the existence of the film boiling regime, which is generally agreed as a necessary initial condition for a vapour explosion, was possible.

Experiments showed that the simulation of the fuel-sodium interaction with the FCI codes requires adequate modelling of the thermo-dynamic properties, the melt-sodium heat transfer, and the effect of the melt solidification. Currently, the applicability of the MC3D code (IRSN, France) to simulate fuel-sodium interaction is under examination. The MC3D code is devoted to the multiphase thermal-hydraulic flow studies and evaluations in the nuclear safety field [4,5]. The major use of the MC3D code is in the evaluation of FCI phenomena in water with two dedicated applications called PREMIX for the simulation of the
premixing phase and EXPLO for the simulation of the explosion phase. To enable the evaluation of fuel-sodium interaction phenomena, the assessment of the implemented sodium tables was already made [6]. Furthermore, the effect of the sodium properties on the heat transfer was assessed and analysed [6,7]. For sodium an improved heat transfer approach was proposed and verified [7]. For testing purpose, an improved heat transfer approach was implemented into the MC3D code version 3.7.3 [7]. The applicability of the MC3D code to simulate the FARO-TERMOS (JRC, Ispra, Italy) experiments was already demonstrated [7]. The analyses of the FARO-TERMOS experimental data and the performed simulations have indicated low probability of a strong vapour explosion in sodium [7].

In the paper, experimentally observed relevant conditions for the vapour explosion in sodium are simulated and analysed in the FARO-TERMOS geometry [3]. The FARO-TERMOS geometry was selected because the experiments performed in the FARO-TERMOS facility could be considered as the most representative case for the sodium cooled fast reactors conditions. In those experiments the largest amount of UO$_2$ was poured into sodium and the occurrence of spontaneous energetic FCI events was reported. Pressure peaks with a maximum value of 6 MPa inside sodium were measured.

The melt-sodium mixing was simulated with the testing version of the MC3D code. In the paper, first the calculation model is described. Second, the comparison of the mixing in sodium and in water is done to assess qualitatively the potential of vapour explosion in sodium. The purpose is to identify the main reasons for the observed strong limitation of the explosion in sodium compared to water. Next, identified experimental parameters characterizing the potential of vapour explosions in sodium are analysed and discussed in a sensitivity study. At the end the conclusions are given.

2 CALCULATION MODEL

In the presented study the initial conditions, the geometry, and the model parameters selection are set based on the FARO-TERMOS T2 data [3] and are fully discussed and justified in [7]. Hereafter, only the information important for this paper are given.

In Figure 1 the applied simplified 2-D geometry is presented. The mesh is axial symmetrical and cylindrical coordinates are used. The mesh has 23x73 cells. The typical cell dimension in the test tube is 8x50 mm$^2$.

![Figure 1: Geometry of computational model.](image)

The UO$_2$ melt pour was modelled as a continuous melt field. The release location was set to 3.75 m. The initial jet release velocity was set to 9.3 m/s. The mean penetration rate of
110 kg/s was used. The specified release rate was achieved by using a release diameter of 0.04 m. The total release mass was set to ~60 kg. The reference temperature of the melt was set to 3300 K. The jet fragmentation into droplets was modelled with a parametric model. The applied constant jet fragmentation rate was defined so that a jet break up length of approximately 1 m was obtained. The reference size of the droplets was set to 1 mm. Secondary break-up of the melt droplets was not considered; therefore the generated droplet size during the jet fragmentation was also the final size of the droplets. The melt droplet quenching was modelled with the crust model that considers the crust thickness on the droplet surface.

Initially the sodium was at 673 K (reference value) and its height in the test section was 2.5 m. The initial pressure in the test section was 0.13 MPa. Argon was used as the cover gas. The volume of the cover gas was 0.15 m$^3$.

### 3 RESULTS AND DISCUSSION

The premixing phase was simulated for 3 s. In Table 1 the main parameters of the base and sensitivity study cases are summarized.

<table>
<thead>
<tr>
<th>Case</th>
<th>Designator</th>
<th>Coolant</th>
<th>Coolant temperature</th>
<th>Melt temperature</th>
<th>Melt droplet size</th>
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<td>water</td>
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<td>3300 K</td>
<td>1.0 mm</td>
</tr>
<tr>
<td></td>
<td>S</td>
<td>sodium</td>
<td>673 K</td>
<td>3300 K</td>
<td>1.0 mm</td>
</tr>
<tr>
<td>Sensitivity</td>
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<td>sodium</td>
<td>1183 K</td>
<td>3300 K</td>
<td>1.0 mm</td>
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<tr>
<td></td>
<td>D−</td>
<td>sodium</td>
<td>673 K</td>
<td>3300 K</td>
<td>0.5 mm</td>
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<td>673 K</td>
<td>3450 K</td>
<td>1.0 mm</td>
</tr>
</tbody>
</table>

#### 3.1 Base study

In the base cases calculations (cases W and S in Table 1) the equal volumes of sodium and water were used. The reference conditions for sodium are presented in Section 2. The initial sub-cooling of water was set to 50 K [8]. The constant fragmentation rate applicable for the FARO-TERMOS conditions was used for both coolants [7]. The size of the melt droplets originating from the jet was the same in both base cases. Namely, similar debris sizes are expected in water and sodium because the differences in the sodium and water density are not so significant. The melt to sodium heat transfer was modelled with the new heat transfer approach [7]. The MC3D default heat transfer model was used for water [4]. The initial cover gas temperature was the same as the coolant temperature.

In Figure 2 the cover gas pressure is given. The position of the cover gas pressure tracking is shown in Figure 1. In general the cover gas pressure in water is 5 to 6 times greater than in sodium. A similar pressure difference was observed also in the energetic events measured at the MFTF facility (Winfirth, UK) [1,2]. In the MFTF tests the same experimental facility with similar experimental arrangements and conditions was used for pouring of molten UO$_2$-Mo into water (SUW series) or sodium (SUS series). The water sub-cooling was ranging from saturated conditions up to 87 K. The sodium sub-cooling was in the range of 419 K to 753 K. In the water experiments the maximal cover gas pressurization of 17.2 MPa and the mechanical yield of 884 kJ was measured. In the sodium experiments the maximal peak cover gas pressurization of 1.97 MPa and the mechanical yield of 137 kJ was measured. Thus a global efficiency of about 6 times greater with water than with sodium was observed for the pressurization during the energetic event.
The main reasons for the observed difference between water and sodium pressurizations in Figure 2 are the differences in the total amount of heat transferred from the melt to the coolant, the coolant boiling, and the vapour condensation. First, for the higher sodium temperature the integral melt to coolant heat transfer is limited more than for the colder water. For example, let us consider the coolant being at saturation conditions at 0.13 MPa – i.e. 1183 K and 380 K for sodium and water, respectively. Then the total available energy for heat transfer per unit of the UO₂ mass is approximately 1.3 times larger for water than for sodium. Second, the combinations of the coolant sub-cooling and the thermo-dynamical properties hinder the boiling stronger in sodium than in water. The energy to vaporize a unit of coolant volume is approximately 1.5 times larger for sodium than for water. Additionally, the saturation pressure strongly limits the sodium boiling if compared to water. For example, the pressure increase from 0.1 MPa to 1.0 MPa changes the boiling temperature for ~330 K in sodium and for ~80 K in water. Finally, the higher sub-cooling and the stronger effect of the pressure increase on the boiling temperature promote the vapour condensation in sodium.

In Figure 3 the total (top) and liquid (bottom) mass of melt droplets are shown. The droplets are considered as liquid when the crust thickness cannot prevent the droplet’s fine fragmentation during the explosion phase. A crust thickness greater than 20% of the droplet radius can be considered as strong enough to prevent any fine fragmentation during a typical FCI explosion phase in water [9]. The masses of droplets are shown for the entire simulated domain (left) and for the regions with void content less than 60 % (right). As seen in Figure 3, the total melt droplets mass stabilizes once the jet inflow is finished. The final maximum droplets mass is lower than the total poured melt mass due to the melt coalescence on the test tube bottom. The majority of the melt droplets are solid. The solidification is faster in sodium than in water. Indeed, as seen in Figure 4, where the premixture development is presented, in water the heat melt quenching is less intensive and the melt droplets remain liquid also when they are in contact with water. For the vapour explosion the so called active mass is the most important – i.e. the mass of liquid droplets in regions with enough coolant available for vaporization and enabling the fine fragmentation process during the explosion phase. As seen in Figure 3 (bottom, right), initially the active mass is larger in water than in sodium. Later, with increasing vaporization the amount of active mass in water is reduced and in sodium it is increased. After the jet fragmentation termination the amount of active mass is reduced in both cases.

The coolant heating up, the vaporization and the condensation affect the active mass and are hereafter used to explain the observed differences in the active mass in Figure 3. The water heating up has smaller effect on the melt quenching, because during typical melt-water interaction conditions the melt quenches only in the film boiling regime [6]. On the contrary, in sodium the melt quenches in the less intensive film boiling regime only when the sodium
temperature is close to the saturation temperature and the melt temperature is still high enough [6]. Otherwise the more intensive transition boiling regime dominates and promotes the sodium heating up and the melt solidification. Therefore the active mass in water is larger than in sodium up to the simulation time of 0.35 s. The sodium heating up promotes the amount of liquid mass. However, the main reason for the observed difference in the time frame between 0.35 and 0.65 s are the sodium saturation pressure property and the large subcooling, affecting the vaporized region. As seen in Figure 4, the vaporized region is larger for water than for sodium. Thus, in water the probability of liquid melt droplets to be in low voided regions is reduced. On the contrary, in sodium the observed local variations of the vaporized region increase the probability of liquid melt droplets to be in low voided regions. Consequently the active mass in sodium increases and in water it decreases. In sodium the largest amount of active mass is obtained around the time of the jet inflow termination (between 0.65 s and 0.85 s). The termination of the jet inflow reduces the vaporization and increases the probability for the vapour region collapse around liquid melt droplets. After the jet fragmentation termination the solidification reduces the active mass in both cases.

To summarize, in general the active masses in sodium and water are comparable. Despite that a weaker explosion is expected with sodium than with water. The main reason is related to the sodium saturation pressure and the significant subcooling, both inhibiting the vaporization during the explosion phase. The reduced vaporization affects the explosion peak pressure and the overall pressurization, as was observed also in the MFTF experiments [2]. The smaller pressure peaks also reduce the rate of the melt droplets fine fragmentation. Therefore, in sodium lower explosion escalation velocities are expected and were eventually also observed in experiments [3].

Figure 3: Base cases. Mass of all droplets (top) and mass of liquid droplets (bottom) in entire simulated domain (left) and in regions with void content less than 60 % (right).
3.2 Sensitivity study

In the sensitivity study the influence of the coolant sub-cooling (case Tc in Table 1), the melt superheat (cases Tm in Table 1), and the melt droplets sizes (cases D in Table 1) were analysed. To study the effect of different melt droplets sizes, the melt inflow conditions had to be varied too, because the droplets size depends on the jet inflow velocity. The jet inflow velocity was thus set inversely proportional to the square root of the melt droplet’s size. The inflow jet cross-section was adjusted to keep the same jet release inflow rate in all cases.

In Figure 5 the total liquid mass of droplets is shown in the test section and in low voided regions. The majority of the melt droplets are solid. The amount of liquid droplets after the jet inflow termination is affected by the coalescence of the liquid droplets on the bottom of the test tube. The coalescence is promoted by lower coolant sub-cooling, higher melt super-heat, and larger size of melt droplets.

As seen in Figure 5, larger amount of active mass is obtained for the saturated case than for the sub-cooled case. Lower sub-cooling inhibits the melt quenching but increases the vaporization. As seen in Figure 6, the size of the vaporized region is larger at saturated conditions (see case Tc+) than at sub-cooled conditions (see case S). Local variations in the vaporised region at saturated conditions reduce the probability of the liquid droplets to be in...
contact with low voided regions. Therefore, at saturated conditions the main contributor to the active mass is the reduced melt quenching at the premixture front. The higher super-heat delays the melt solidification and increases the active mass. The variation of the jet inflow conditions has a strong effect on the active mass. The main contributor to the amount of the active droplets is the increasing solidification time and the decreasing vaporization rate with the increasing droplet size.

To summarize, all studied parameters have an effect on the solidification and the vaporization. Lower coolant sub-cooling, higher melt super-heat, and lower jet impact velocity inhibit the melt droplet solidification and thus promote the amount of the active mass.

Figure 5: Effect of coolant sub-cooling (top), melt super-heat (middle) and jet inflow conditions (bottom). Mass of liquid droplets (left) and mass of active droplets (right).
4 CONCLUSIONS

In the paper the potential of vapour explosions in sodium was investigated in the FARO-TERMOS geometry and conditions.

The premixing simulation results demonstrate the lower potential for vapour explosion in sodium than in water. The most important differences between the sodium and water simulation results are in the cover gas pressure. The main reasons for the discrepancy are the differences in the saturation pressure and sub-cooling. For sodium the saturation pressure curve limits the boiling stronger than for water. Therefore the pressure during the explosion phase is expected to be limited for sodium to moderate pressures of few MPa. Also the significantly larger sub-cooling in sodium inhibits the strong vaporization during the explosion phase. Although no significant difference between the active mass in water and sodium was observed, it was assessed that the explosion would be weaker for sodium due to the lower pressurization during the explosion phase.

The main purpose of the sensitivity study was to define the conditions for the maximized vapour explosion potential. The coolant at saturation conditions in combination with the higher melt superheat and the lower melt inflow velocity promotes the amount of active mass and the time range for its availability to participate in the explosion phase. Although similar amount of active mass could be also obtained at sub-cooled conditions those conditions are less favourable for the development of a strong explosion because of the active mass dependence on the stability of the vaporized regions. Moreover the sub-cooled conditions are expected to result in weaker explosions also due to the energy needed for the coolant heat-up and the increased condensation during the explosion phase.

Based on the simulation results the selection of the near saturation conditions, moderate jet impact velocities and higher melt super-heating is suggested to be used as the initial conditions for future experiments for the investigation of the explosion potential. The saturation conditions would potentially increase the probability to start the explosion phase with the maximized amount of the active mass. Because saturated conditions would inhibit the film destabilization around the droplet, which is considered as a potential spontaneous vapour explosion triggering mechanism, the use of artificial explosion triggering might be considered in such experiments.
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REFERENCE