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PREDICTION OF MASS FRACTION OF AGGLOMERATED DEBRIS IN A LWR SEVERE ACCIDENT

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Abstract

Ex-vessel termination of accident progression in Swedish type Boiling Water Reactors (BWRs) is contingent upon efficacy of melt fragmentation and solidification in a deep pool of water below reactor vessel. When liquid melt reaches the bottom of the pool it can create agglomerated debris and "cake" regions that increase hydraulic resistance of the bed and affect coolability of the bed. This paper discusses development and application of a conservative-mechanistic approach to quantify mass fractions of agglomerated debris. Experimental data from the DEFOR-A (Debris Bed Formation and Agglomeration) tests with high superheat of binary oxidic simulant material melt is used for validation of the methods. Application of the approach to plant accident analysis suggests that melt superheat has less significant influence on agglomeration of the debris than jet penetration depth. The paper also discusses the impact of the uncertainty in the jet disintegration and penetration behavior on the agglomeration mode map.

Introduction

Reactor cavity flooding has been adopted as a means for termination of ex-vessel severe accident progression in Swedish type Boiling Water Reactors (BWRs). It is assumed that melt fragmentation and formation of a porous debris bed coolable by natural circulation will take place in a deep pool of water. Non-coolable debris bed presents a credible threat to containment integrity. Present work pertains to the DEFOR (Debris Bed Formation) research program [1]-[11] initiated at the Division of Nuclear Power Safety (NPS) Royal Institute of Technology (KTH). The aim of the DEFOR program is clarification of the phenomena that govern formation of the debris bed in different scenarios of corium melt release into a deep pool of water and quantification of the debris bed properties and scenario parameters that govern coolability of the bed.

Agglomeration of debris and "cake" formation can occur if significant fraction of the melt is in liquid state at the time when the melt reaches the floor of the lower drywell. Formation of agglomerated debris and "cake" regions that increase hydraulic resistance of the bed can negatively affect coolability of the bed [11]. Until recently, debris agglomeration and cake formation have not been studied systematically, although these phenomena have been reported in different tests with prototypical corium melts (e.g. in [12], [13]), as well as in the tests with corium simulant materials (e.g. in [3], [7], [8]).

A concept of agglomeration mode map has been proposed in [4] for prediction of debris agglomeration in different plant accident conditions. A conservative-mechanistic approach to quantify the mass fraction of agglomerated debris was developed in [5]. The approach has been validated in [6] against several DEFOR-A (Debris Bed Formation and Agglomeration) tests [8]. The approach combines (i) deterministic code VAPEX [14], [15], [9], which is used as a computational vehicle for the simulation of the fuel coolant interaction (FCI) phenomena including jet breakup, formation of liquid droplets, sedimentation and solidification of the particles, with (ii) conservative assumptions in modeling, which are used to bound intrinsic epistemic uncertainties in physical phenomena. The sensitivity of predicted mass fraction of agglomerated debris to different assumptions in modeling (epistemic uncertainty) and to different uncertain parameters of scenario (aleatory uncertainty) of melt-coolant interaction was studied in [6]. Specifically the influence of jet breakup mode and effect of modeling of inter-phase heat transfer and resulting steam production rate in the melt-coolant interaction zone were considered. It was demonstrated that conservative treatment of the uncertainties creates sufficient margin and simulation data are enveloping the set of mass fractions of agglomerated debris obtained at various experimental conditions.

Most of the DEFOR-A tests used for validation were performed at ~100 K melt superheat. Data from DEFOR-A7 [8] and DEFOR-A9 performed at ~200 K melt superheat suggest that at higher melt superheat the fraction of agglomerated debris increases significantly at the same depth of water. The goals of the present work are (i) to validate the conservative-mechanistic approach against DEFOR-A tests with high (~200 K) melt superheat, and (ii) to quantify the sensitivity of the mass fraction of agglomerated debris to plant accident conditions including initial melt superheat.

1. Conservative-mechanistic approach to prediction of mass fraction of agglomerated debris

Three different modes of agglomeration were defined in [4] according to their potential impact on coolability:

1) No agglomeration. The bed consists of completely fragmented debris.

2) Agglomerated debris. The bed consists of partially agglomerated debris connected by inter-particle bonds.

3) Cake. The bed represents a chunk of solidified melt with no open porosity for coolant ingression into the cake interior.

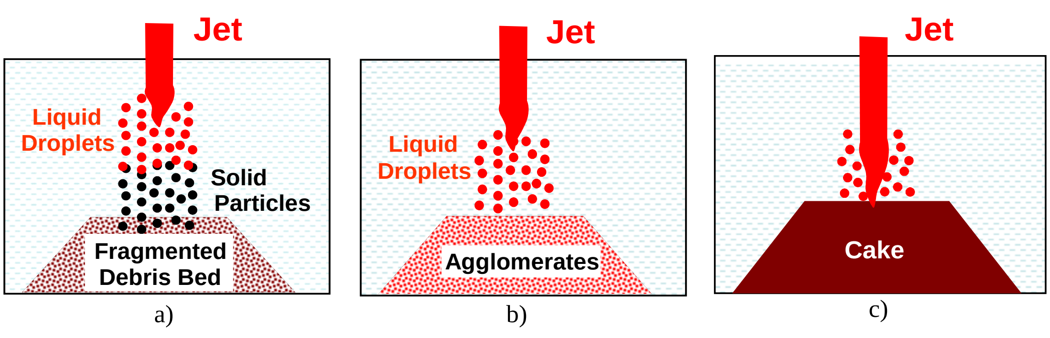


Figure 1 Modes of debris agglomeration: a) fragmented debris; b) agglomerated debris; c) cake.

Conservative assumptions about the conditions for onset of the different modes of the debris agglomeration are discussed in [4], [5], [6]. Namely, we assume that agglomeration modes are defined by the state of the melt fragments right before depositing (pre-deposition state) on top of the debris bed as shown in Figure 1. No-agglomeration (first mode, Figure 1a) is expected when melt particles already have a thick crust when they are depositing on the top of the bed. Partial agglomeration (second mode, Figure 1b) is expected when some fraction of the debris may reach the top of the debris bed in the form of liquid droplets. A cake is formed when jet breakup length is greater than or equal to the depth of the water pool (third mode, Figure 1c).

We assume that agglomeration is a result of interactions between partially liquid droplets with each other and with neighboring solid particles [4], [5], [6]. The jet breakup phenomena affect agglomeration phenomena only by providing “initial conditions” in terms of fraction of fragmented liquid melt at certain depth. Then, melt droplet solidification processes affect distribution of relative crust thickness, which in turn defines mass fraction of agglomerated debris. It is further assumed that mass fraction of agglomerated debris is proportional to the mass fraction of completely liquid droplets and thin-crust particles (“liquid” or “glue” particles) [5], [6].

$$m_{aggl} = \alpha \cdot m_{liq} \tag{1}$$

where m_{aggl} is mass fraction of agglomerated debris, m_{liq} is mass fraction of liquid particles (with relative crust thickness less than 0.1), $\alpha = \alpha(m_{liq})$ is coefficient of agglomeration, which is a function of mass fraction of the liquid particles. Even if measurement of m_{liq} in pre-deposition state of the debris would be feasible, one could expect significant scatter of experimentally determined values of agglomeration coefficient α. Therefore, it was suggested to use a bounding assessment rather than a best estimate for the coefficient of agglomeration α [5], [6]. The purpose of using bounding assessment for α is to ensure conservative but physically reasonable prediction of fraction of agglomerated debris, taking into account inherent epistemic uncertainties in the jet breakup and agglomeration phenomena. Conservative estimate of the fraction of agglomerated debris provides initial conditions for conservative assessment of the debris bed coolability.

The procedure for deriving the bounding assessment includes three steps. First, simulations are performed to calculate fractions of liquid particles m_{liq}^{j} at given experimental conditions. We use different bounding assumptions about epistemic uncertainties in the modeling of melt-coolant interactions and about the variations of uncertain physical properties of the melt [5], [6]. Second, a set of values $\alpha_{ij} = m_{agl}^{j} / m_{liq}^{i}$ is calculated by combining data about m_{liq}^{j} from the simulations with the data about mass fraction of agglomerated debris m_{agl}^{i} from DEFOR-A experiments. Third, the coefficient of agglomeration α is defined as a curve which envelops the domain covered by the set of α_{ij} values [5], [6], providing bounding assessment which takes into account both uncertainties in mechanistic modeling of melt-coolant interaction phenomena and in the physical properties of the melt. The following enveloping assessment for the coefficient α is proposed in [5], [6]

$$\alpha(m_{liq}) = \begin{cases} 4 \cdot m_{liq}, & m_{liq} \le 0.5 \\ 1/m_{liq}, & m_{liq} > 0.5 \end{cases} \tag{2}$$

We also consider formula (3) to assess how sensitive is predicted mass fraction of agglomerated debris in experimental scale problem and in plant scale analysis to variations in enveloping assessment of α.

$$\alpha(m_{liq}) = \begin{cases} 25/4 \cdot m_{liq}, & m_{liq} \le 0.4 \\ 1/m_{liq}, & m_{liq} > 0.4 \end{cases} \tag{3}$$

2. The validation of the approach against the DEFOR-A experimental data

2.1 Test cases parameters and assumptions in modeling

The goal of the validation in the present work is to demonstrate that the developed approach provides a robust bounding but physically reasonable assessment of the fraction of agglomerated debris despite the inherent uncertainties in the physical phenomena. This goal differs from the standard goal for validation of a best estimate code when a "best match" between experimental and simulation data is the aim.

All DEFOR-A [8] tests conditions and results on mass fraction of agglomerated debris are summarized in Table 1 and Figure 2. The proposed conservative-mechanistic approach has been validated [6] against DEFOR-A tests with melt superheat about 100 K. In this work, we use DEFOR-A7 and DEFOR-A9 tests with 200 K of melt superheat for validation of the approach.

Table 1. Test parameters and DEFOR-A experimental data

Parameters	Tests							
	A1	**A2**	**A4**	**A5**	**A6**	**A7**	**A8**	**A9**
Melt temperature, K	1253	1246	1221	1245	1279	1349	1255	1343
Melt superheat, K	110	103	78	102	136	206	112	200
Melt jet initial diameter, mm	10	20	20	10	12	25	25	20
Duration of melt release, s	38	11	11	38	20	10	10	11
Elevation of melt release, m	1.7	1.7	1.7	1.7	1.7	1.62	1.62	1.7
Jet free fall height, m	0.18	0.18	0.20	0.18	0.18	0.20	0.20	0.18
Water pool depth, m	1.52	1.52	1.50	1.52	1.52	1.42	1.42	1.52
Water initial temperature, K	346	367	346	364	346	356	355	355
Water subcooling, K	27	7	27	9	27	17	18	18

The same conditions as specified in Table 1 are used in simulations. The following values of melt properties are assumed in all simulations: density 7811 kg/m^3; eutectic melt with melting temperature 1143 K; fusion heat 83 kJ/kg; heat capacity 280 J/(kg·K); thermal conductivity 5.3 W/(K·m); melt mass 23.43 kg. Sensitivity study performed in [5] shows that the effect of the uncertainties in the melt properties on the prediction of m_{aggl} is relatively small in comparison with the effect of the jet breakup mode or model for melt-water-steam heat and mass transfer. We use fixed particle size distribution presented in Figure 3 (size distribution of the particles collected in all DEFOR-A tests) to reduce uncertainties in the analysis related to the droplet fragmentation models. The influence of epistemic uncertainties in modeling of (i) jet breakup, and (ii) steam production rate in the melt-coolant interaction zone on fraction of agglomerated debris has been addressed in [6]. Significant influence of the model for the jet breakup mode (Rayleigh-Taylor (denoted as "RT") instability or Kelvin-Helmholtz (denoted as "KH") instability) on the result of calculation of the mass fraction of agglomerated debris has been identified. It was demonstrated that the most conservative estimate of the fraction of agglomerated debris for the DEFOR-A test conditions is predicted with KH model, therefore we use KH model in this work.

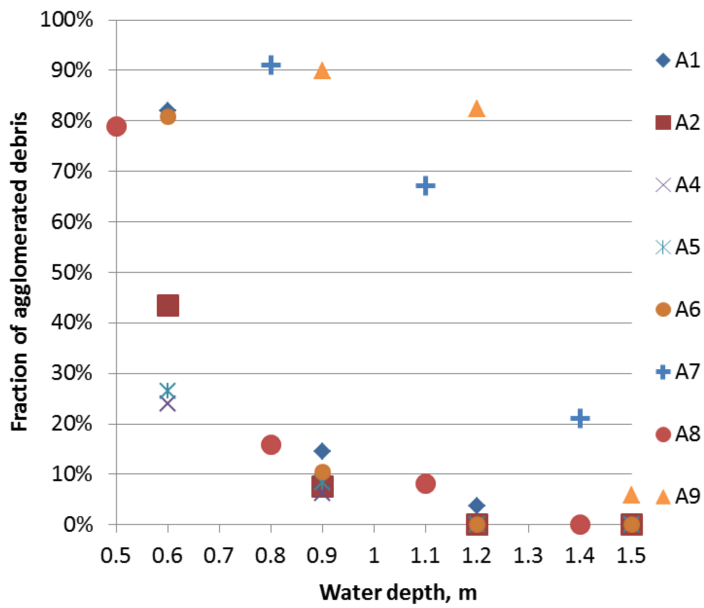


Figure 2 The mass fraction of agglomerated debris in DEFOR-A tests

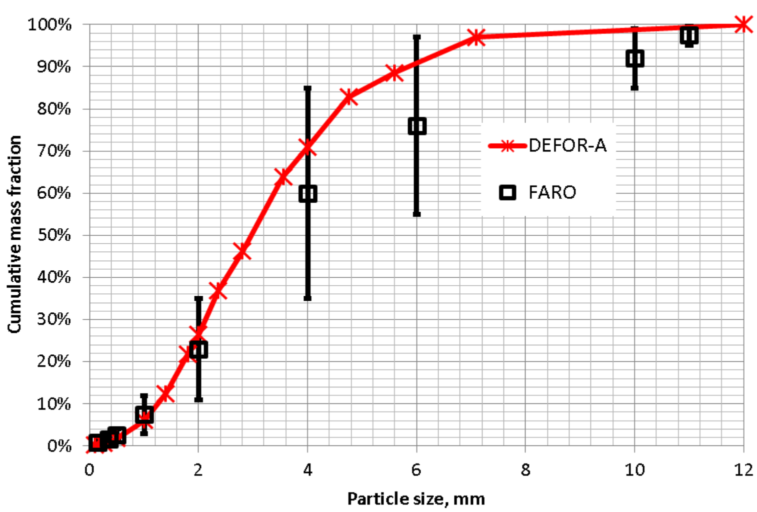
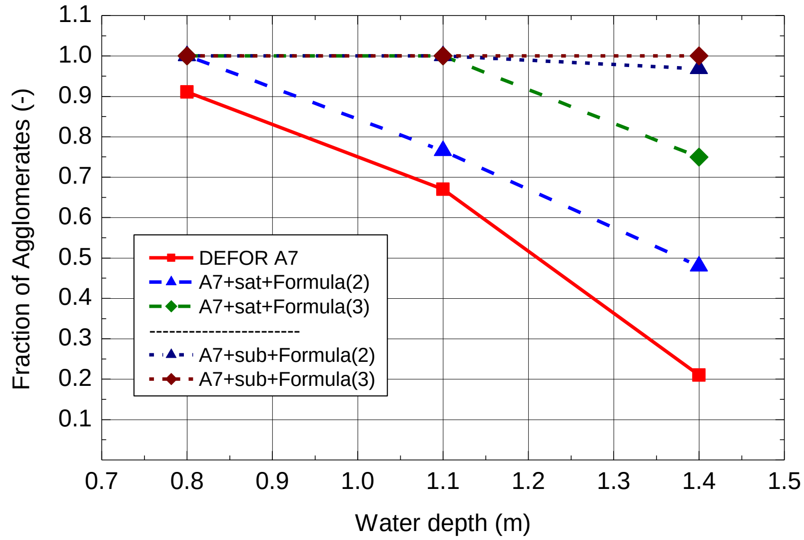


Figure 3 Size distribution of the particles collected from all DEFOR-A experiments (red line). Variations of particle-size distribution obtained in FARO tests are also shown for comparison in black.

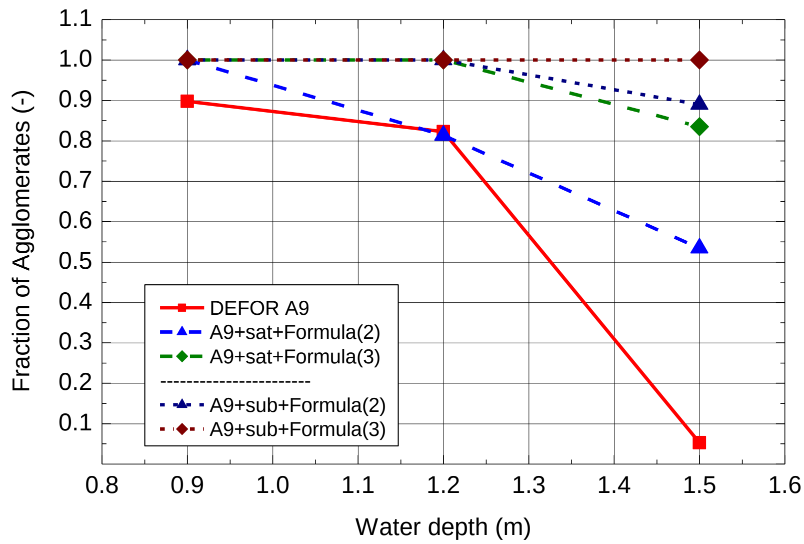
Two bounding assumptions in modeling of steam production rate were also examined in [6]. In the first case, denoted as "sat", all heat released by the melt goes to evaporation of the water (as in saturated water). In the second case, denoted as "sub", all heat released by the melt goes only to heating of water and all locally generated steam condenses immediately (as in deeply subcooled water).

2.2 The validation against the DEFOR-A data with high melt superheat

Mass fractions of agglomerated debris from the DEFOR-A tests are presented in Figure 2 as function of water pool depth. Apparently, the melt superheat is the most influential parameter for the fraction of agglomerated debris within the ranges of parameters considered in the DEFOR-A tests. The biggest values of the mass fraction of agglomerated debris are observed in DEFOR-A7 and DEFOR-A9 at about 200 K melt superheat. However, it is important to mention that fraction of agglomerated debris reduces rapidly as a function of the water pool depth even in the test with high melt superheat.



a)



b)

Figure 4 Validation against experimental data: a) DEFOR-A7; b) DEFOR-A9.

Results of the validation against DEFOR-A7 and DEFOR-A9 tests data are presented in Figure 4. It can be seen that predicted values of agglomerated debris provide conservative estimates even if "sat" assumption is used in modeling of the inter-phase heat transfer. In our previous work [6] we discussed the physical reason for the formation of lower fraction of agglomerated debris in case of saturated water in the DEFOR-A test conditions. Also important is that predicted fraction of agglomerated debris reduces rapidly with the pool depth similarly to those measured in the experiments. Results of validation suggest that the developed conservative-mechanistic approach can conservatively predict the fraction of agglomerated debris. The conservatism is necessary is necessary for plant scale analysis to envelop the effect of possible uncertainties in physical phenomena or accident scenarios.

Figure 5 summarizes the data about dependency of mass fraction of agglomerated debris on the mass fraction of liquid particles obtained for all DEFOR-A tests and simulation conditions. Bounding estimates obtained according to (1) with the formulas for coefficient of agglomeration (2) and (3) are presented in Figure 5. It is clear that both formulas (2) and (3) provide enveloping estimates for the semi-empirical set of data on the mass fraction of agglomerated debris including the tests with high melt superheat. We use formula (2) for analysis of agglomeration in the plant accident conditions.

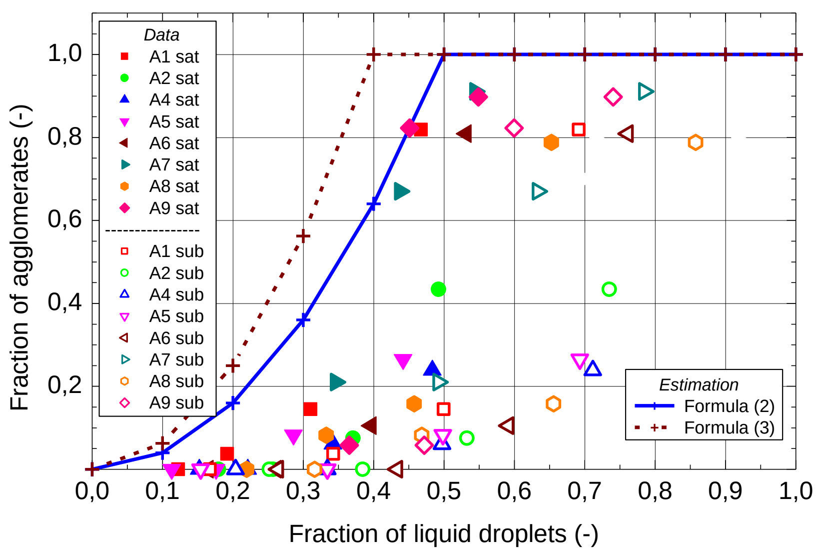


Figure 5 Conservatism in the estimation of the mass fraction of agglomerates. All cases are calculated with Kelvin-Helmholtz (KH) jet breakup mode: "sub" – "subcooled" water assumption; "sat" – saturated water assumption.

3. Application of the approach to plant accident analysis

3.1 Influence of modeling of jet breakup mode and melt-water-steam heat transfer in plant-scale simulations

Results of simulations for development of agglomeration mode map for a Nordic BWR accident conditions are presented in this section. Main parameters for the calculations are presented in Table 2. In addition to that, we use following assumptions in the modeling:

1) Fixed size distribution of the debris measured in DEFOR-A tests (Figure 3) was used in the modeling in order to reduce the influence of epistemic uncertainty in the modeling of melt droplet fragmentation. Comparison of data from different FCI tests with simulants [8] and prototypical corium mixtures [12] suggests that size distributions of heavy binary oxide ceramics particles are close to each other despite sometimes significant differences in the experimental conditions (melt material and temperatures, jet diameter, jet free fall height etc.). However, further analysis might be necessary to assess the sensitivity of the faction of agglomerated debris to possible variations in the size distribution of the particles;
2) According to realistic geometry of a Nordic BWR the distance from the bottom of reactor vessel to the floor of reactor cavity was kept equal to 13 m. Thus height of the melt jet free fall decreases when the depth of the pool is increasing;
3) Prototypic geometry of the vessel lower-head is taken into account in assessment of the melt pool depth (1.75 m) according to the total mass of the pool (180 tons).

Previous simulations results discussed in [6] show that combination of “sat+RT” assumptions provides highest fraction of liquid particles (with relative crust thickness less than 0.1) in plant scale analysis. Therefore, this combination of modeling assumption was also used in present work for the sake of conservatism in the analysis. Calculations were performed upon reaching a quasi-steady state (total mass of particles present in the pool volume and mass distribution of particles with different relative crust thickness that have deposited on the bottom of the pool are reaching a maximum and not changing considerably with time). It is worth mentioning that interaction between melt and coolant never reaches pure steady state because (i) the level of the melt in the vessel is decreasing, while (ii) water pool temperature is growing during the pouring process. The last leads to reduction of heat transfer rate from melt droplets to water, however it has negligible impact due to the large volume of the water pool. The first effect leads to decrease of the initial jet velocity and subsequent jet penetration depth. Reduction of the jet penetration length can be quite fast, especially in case of a large diameter of the jet. Jet penetration depth is the major factor that defines the onset of cake formation regime and the mass fraction of agglomerated debris at the pool bottom. The proposed approach provides a bounding conservative estimate because we calculate fraction of agglomerated debris during the first part of the transient when jet penetration depth and fraction of liquid particles at the pool bottom are bigger than the averaged values for the whole transient.

Table 2 Plant accident conditions.

Parameter	**Value**
Pool parameters	
Diameter, m	9
Depth, m	7-12
Initial pressure, bar	1
Water temperature, K	373
Melt parameters	
Composition	Eutectic corium
Total mass, t	180
Initial temperature, K	3000-3200
Initial met superheat, K	200-400
Jet diameter, mm	50-300
Jet release height, m	1-6

The influence of melt superheat on the fraction of agglomerated debris in reactor accident conditions was considered for the following cases:

1) "Base case"–melt superheat 200 K;
2) "Sup" case –melt superheat 300 K;
3) "Sup+" case –melt superheat 400 K.

We consider relative crust thickness $\delta_{rel} = \delta_{crust}/R_{drop}$, (where δ_{crust}–absolute crust thickness, R_{drop} – radius of the particle) as quantitative characteristics of the debris pre-deposition state. The results of "Base case" calculations for the mass fraction distributions of particles with different relative crust thicknesses are presented in Figure 6, Figure 7 and Figure 8 respectively for pool depths H_{pool}=7, 9 and 12 m.

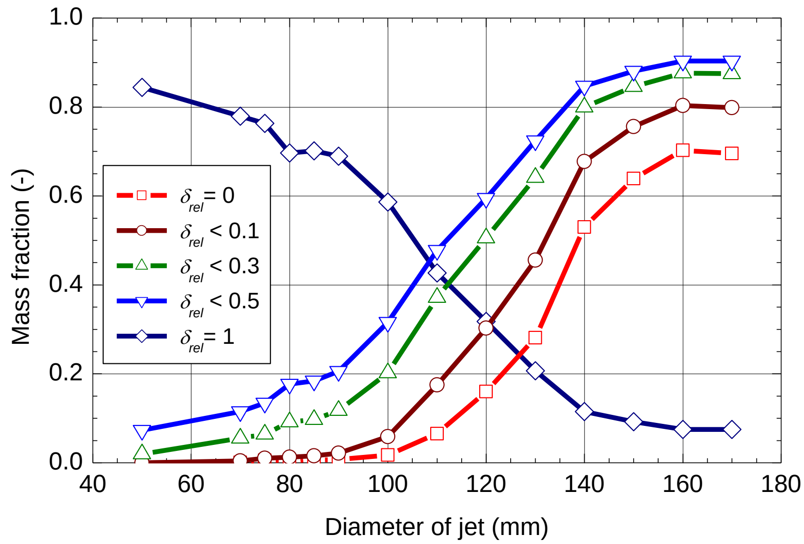


Figure 6 Mass fractions of particles with different relative crust thicknesses as functions of jet diameter, H_{pool}=7m, Base case.

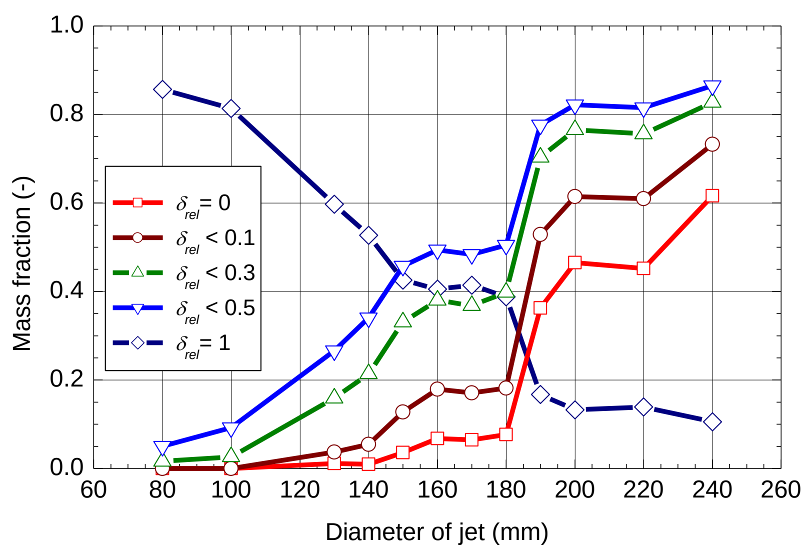


Figure 7 Mass fractions of particles with different relative crust thicknesses as functions of jet diameter, H_{pool}=9m, Base case.

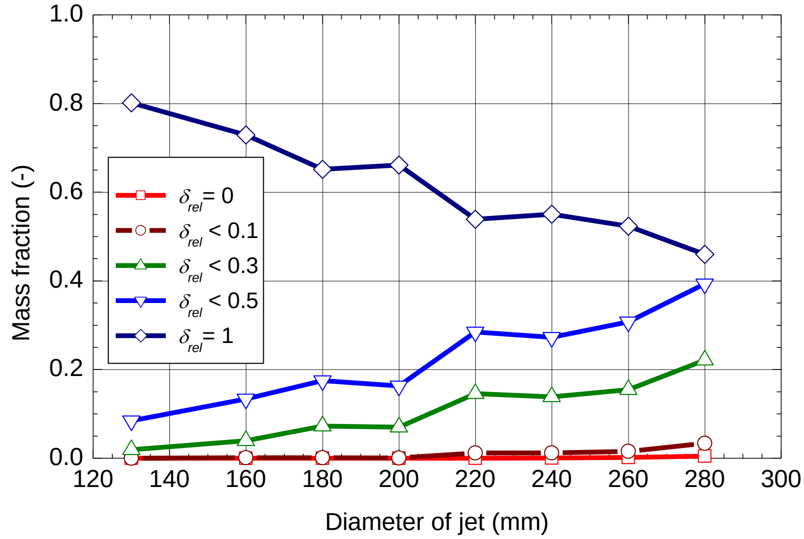
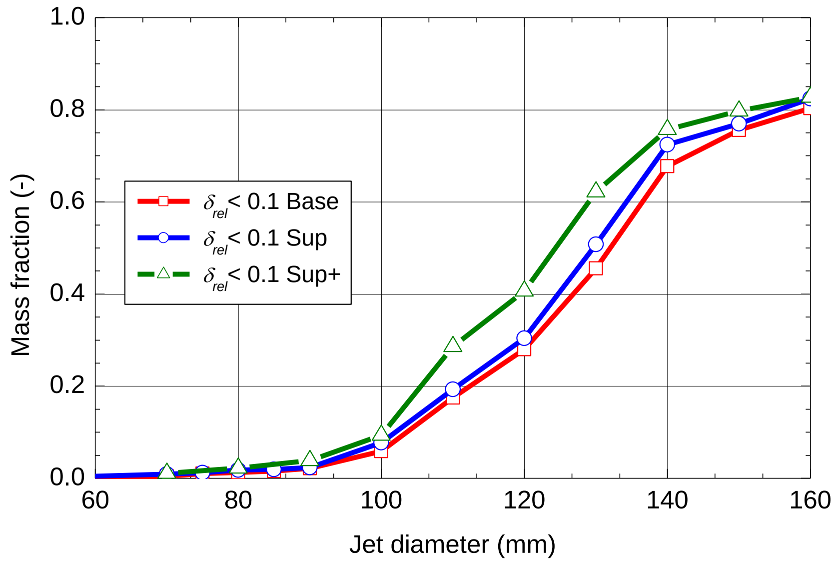


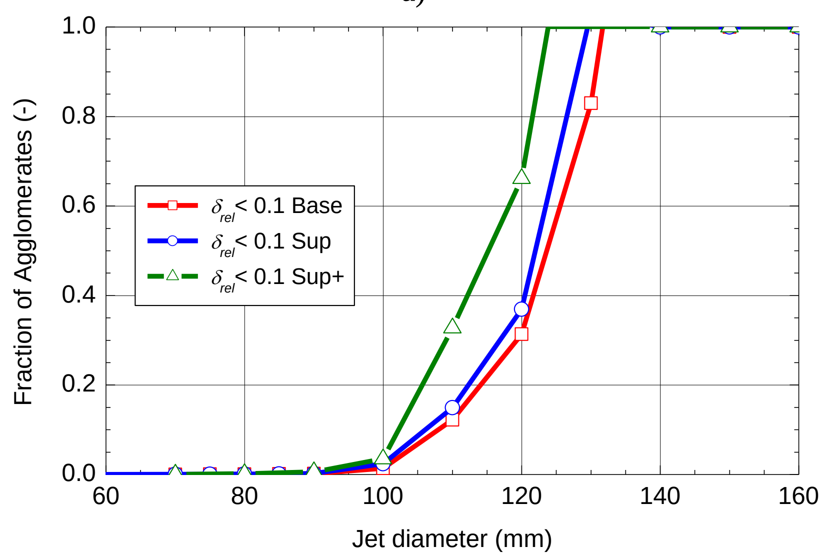
Figure 8 Mass fractions of particles with different relative crust thicknesses as functions of jet diameter, H_{pool}=12m, Base case.

Simultaneous reduction of the jet free fall height and increase of the pool depth has significant effect on the fraction of “liquid” particles ($\delta_{crust} < 0.1$) as is shown in the figures. The free fall height of the jet is only 1 m in case of 12 m deep pool. Resulting jet entrance speed is considerably smaller than in case of 7 m deep pool (6 m free fall height). Slower jet entrance velocity gives smaller jet penetration depth for the same jet diameter. For example, jet with diameter about 300 mm is completely disintegrated at about 3 m above the bottom of the 12 m deep pool. If solidification length (the length of the particle trajectory that is necessary to form a thick crust on the surface of initially liquid droplet falling down in the pool) for corium particles is shorter than 3 m, then particles have enough time to form a thick crust and solidify before deposition at the bottom of the pool preventing formation of the agglomerates. Data presented in Figure 8 suggest that the mass fraction of liquid droplets is very low at the pool bottom in 12 m pool case and no agglomeration is expected with quite big sizes (up to about 300 mm) of the vessel breach.

Comparison of the mass fractions of “liquid” particles ($\delta_{crust} < 0.1$) and respective fraction of agglomerated debris obtained at different melt superheats in a 7 m deep pool are shown in Figure 9. Apparently, the influence of melt superheat on pre-deposition state of the debris and eventually on the fraction of agglomerates is not as big as in the DEFOR-A experimental conditions. The main reason is that in the plant accident conditions the ratio of solidification length to jet breakup length is considerably smaller than that for the DEFOR-A test conditions. Therefore, the effect of increase in the solidification length is much more visible in DEFOR-A tests, and less important for the plant. Nevertheless, even in the plant conditions, there is a clear tendency towards increase of the fraction of “liquid” particles with increase of the melt superheat, especially in the range from 0% to 20% of “liquid” particles. Fraction of agglomerated debris increases rapidly, because it is proportional to the square of the liquid particle fraction, which is increasing as the jet diameter (and thus jet length) is increasing. At higher fractions of “liquid” particles (above 20%) jet penetration depth is already close to the pool depth, which defines onset of the “cake” mode of agglomeration. Similar qualitative results were obtained also for the other depths of the pool.



a)



b)

Figure 9 Mass fractions of liquid particles (a) and agglomerates (b) for H_{pool}=7m.

Two correlations, that are considered in the present work, can be considered as a lower bound (Taylor correlation [17]) and an upper bound (Saito correlation [16]) respectively. Taylor correlation suggests that non-dimensional jet breakup length depends only on the ratio of the densities:

$$L/D = 5.3\sqrt{\rho_m/\rho_w}$$

Saito correlation takes into account the velocity of the jet at the entrance to the coolant:

$$L/D = 2.1\sqrt{Fr}\sqrt{\rho_m/\rho_w}$$

where L - jet breakup length, D - diameter of the jet at the entrance to the coolant, ρ_m - density of the melt, ρ_w - density of the coolant, $Fr = u^2/gD$ - Froude number, u - jet velocity at the entrance to the coolant.

VAPEX code uses Saito correlation for determining the jet breakup length. Taylor correlation provides constant dimensionless length of the jet breakup for the plant accident conditions: L/D~14. Saito correlation predicts jet breakup length L/D~54, 45 and 32 for the jets reaching the bottom of 7, 9 and 12 m deep pools respectively. That is approximately 4, 3 and 2 times bigger than L/D according to Taylor correlation. In case of 7 m deep pool, the difference between jet lengths calculated according to these correlations is more than 3-4 m. The difference can be even bigger for deeper pools (e.g. about 6 m in case of 12 m pool). Solidification length, which also can be defined as the distance between the leading edge of the jet and the depth at which agglomeration becomes negligible, for the DEFOR-A conditions is about 1.0 m at maximum according to the experimental data. For the plant accident conditions, the solidification length is about 1.5 – 2.0 m according to the simulations presented in Figure 10. When possible variations (3 – 6 m) in the jet breakup length are compared with the total solidification length (up to 2 m), it becomes obvious that epistemic uncertainty in jet breakup modeling is currently dominating over other sources of uncertainties, which can contribute to the variation in the fraction of agglomerated debris.

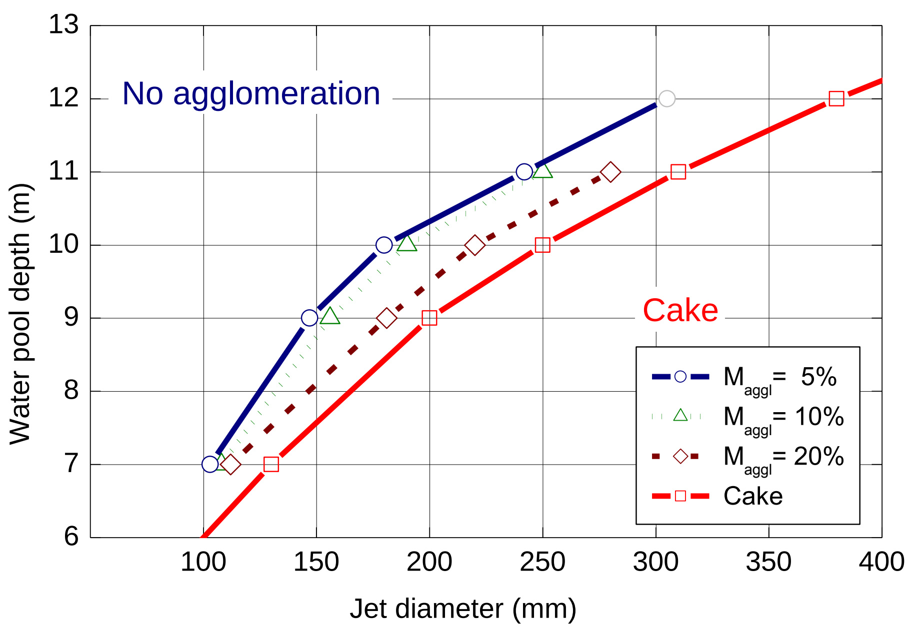


Figure 10 Agglomeration mode map.

If Taylor correlation would be used in the analysis of agglomeration, then no agglomeration would be expected with jet diameters smaller than 350 mm, 500 mm and 700 mm for 7, 9 and 12 m deep pools respectively. These values of “safe” breach size are considerably larger than possibly over-conservative values obtained with Saito correlation. Unfortunately, the scatter of available experimental data on L/D at different tests conditions and absence of real consensus on approach to modeling of jet breakup phenomena (e.g. [18], [19]) hinder further reduction of the conservatism in the analysis.

The main implication of the present results is that melt superheat has less significant contribution to the uncertainty in the debris agglomeration than jet breakup length. Liquid droplets, once formed, solidify quite fast. No significant agglomeration is expected if there is more than 2 meters between the leading edge of the melt jet and the top of the debris bed.

Results of the plant accident analysis obtained with Saito correlation are summarized in the form of the agglomeration mode map in Figure 10. Red line represents the boundary of “cake” domain, other lines in the figure represent cases of partially agglomerated debris bed with 5%, 10% and 20% mass fraction of agglomerates calculated by formulas (1) and (2).

4. Conclusion

Agglomeration of core melt debris can hinder melt coolability reducing reliability of severe accident mitigation strategy adopted in Nordic BWRs, where melt is expected to fragment and form a coolable porous debris bed in a deep pool of water located below the reactor vessel. In this work, a conservative-mechanistic approach to prediction of mass fraction of agglomerated debris has been further developed and validated against DEFOR-A tests data with simulant melt superheat up to 200 K. Validated models along with conservative assumptions are used for development of an agglomeration mode map at different plant accident conditions. Performed analysis suggests that debris bed formed few meters below the leading edge of the jet will be completely fragmented. This finding is also supported by experimental observations in the DEFOR-A tests. The influence of the pool depth, initial jet diameter and melt superheat on resulting mass fraction of agglomerated debris is considered in this work. It is concluded that epistemic uncertainty in the modeling of the jet breakup length is currently dominating over the other sources of epistemic and aleatory uncertainties. It is suggested to undertake further the efforts on reduction of potentially excessive-conservatism in the jet breakup length and on clarification of potential influence of the other possible sources of uncertainty such as particle size distribution.

Acknowledgements

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