EFFECT OF PARTICLE SPREADING ON COOLABILITY OF EX-VESSEL DEBRIS BED

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ABSTRACT

Debris bed formation and coolability are studied by DECOSIM code. Main physical mechanisms affecting dispersed particle spreading in the course of melt-water interaction are considered, and their relevance to the formation of porous debris bed in various melt ejection modes is discussed. Numerical simulations of gradually growing and instantly formed debris beds are performed by DECOSIM code. Also, coupled simulations are carried out in which all mechanisms are taken into account simultaneously. It is shown that particle spreading limits the height of debris bed. Also, it is obtained that in some parameter ranges even if local dryout occurs, further particle spreading can render the debris bed coolable, resulting in its reflooding and quenching of the material.

KEYWORDS
Severe accident, debris bed, coolability, two-phase flow, particle spreading

1. INTRODUCTION

Severe accident on nuclear reactor may progress into the stage where molten corium is ejected from failed reactor pressure vessel, posing significant threat to containment integrity. The severe accident management strategy adopted in Nordic-type boiling water reactors is to provide a deep water pool in which the molten core material can be fragmented and cooled in the form of an ex-vessel debris bed. An important safety issue arising is whether passive cooling by the pool water will be sufficient to remove the decay heat released in corium in order to prevent debris bed dryout and remelting in the pool (debris bed coolability problem) [1]. Research into ex-vessel debris bed coolability clearly indicates that critical conditions under which the porous material is cooled without local dryout depend on the debris bed properties (mean particle diameter, porosity), operating conditions (system pressure), as well as on the debris bed shape.

A tall debris bed consisting of small particles is going to be the most vulnerable to dryout. There exist, however, physical mechanisms that can limit the possibility that such a combination can occur. Two such mechanisms related to particle redistribution during debris bed formation and further evolution are studied in this work: i) spreading of falling melt particles in the pool by natural convection flows arising due to vapor release in the debris bed; ii) spreading of settled particles due to fluidization of the top layer of porous material. The former mechanism is effective when melt release from the vessel occurs gradually, in which case debris bed formation takes long enough time for natural circulation to affect melt particles as they fall in the pool. The latter mechanism may be effective even in the case of massive melt release, unless a “cake” is formed on top of the bed.

In this work, debris bed formation and coolability are studied by DECOSIM code. Both particle spreading mechanisms are considered separately, in simulations of gradually growing and instantly formed debris beds. Also, coupled simulations are carried out in which both mechanisms are taken into account simultaneously. It is shown that particle spreading limits the height of debris bed. Also, it is obtained that in some parameter ranges even if local dryout occurs, further particle spreading can render the debris bed coolable, resulting in its reflooding and quenching of the material.

2. MATHEMATICAL MODEL

We consider, in the coupled manner, transient formation of an ex-vessel porous debris bed from corium melt particles released from the failed reactor vessel, lateral particle spreading due to partial fluidization of the top layer of the debris bed material, as well as boiling two-phase flow in the debris bed due to decay heat release in corium. Below, the key elements of the mathematical model are presented.

2.1. DECOSIM Overview

Numerical simulations are carried out by DECOSIM code developed at KTH for severe accident analysis. The code is capable of simulating two-phase flows in heat-releasing porous medium, as well as multiphase turbulent flows in water pool. The code was applied to the coupled analysis of debris bed formation in saturated [2] and subcooled [3] water pools, as well as to coolability studies, including pre and post-dryout behavior [4]. Here, a short overview of the mathematical models and their numerical implementation is given, details can be found in [2–4].

DECOSIM relies on the multi-fluid governing equations for the boiling flows. Two distinct flow subregions are considered: the porous medium flow in the debris bed, and free turbulent flow in the pool. Two-fluid model is applied to liquid coolant and vapor phases. In the porous medium, the flow is dominated by the balance between the pressure gradient and drag, while in the free flow full momentum equation is solved for each phase. To facilitate numerical implementation, the equations are formulated in a unified manner, with relevant terms set to zero depending on whether the current point is in the porous medium or in the ambient flow. The flow can be simulated either under the saturated conditions assumption, or in the full formulation where energy equations are solved for each phase. Recently, DECOSIM was extended to take into account interaction with solid structures necessary for tackling in-vessel coolability problems in the scenarios where core degradation results in a porous in-vessel debris bed formation [5].

The key elements of DECOSIM relevant to the current study are the capability of predicting particle sedimentation and packing in the gradual melt release mode, allowing one to treat debris bed formation and “self-organization” of particles by interaction with the natural convection flows developing in the pool due to vapor release in the debris bed [2, 3], as well as prediction of two-phase flow in the porous debris bed, including possible dryout or reflooding [4] due to gradual decrease in the decay heat power or due to the changes in the debris bed shape. The new feature implemented in the course of this work is the model for lateral spreading of particles according to the “self-leveling” mechanism due to partial fluidization of the top particle layer.

2.2. Debris Bed Properties and Geometry

We consider a large water pool of 12 m diameter and maximum water depth 9 m, as prototypical for Nordic-type BWRs. In the adopted severe accident management strategy (SAM), the pool is filled with water from the pressure suppression pool. Depending on the accident scenario, operator actions on implementation of the emergency operation procedures (EOPs) and SAM Guidelines (SAMGs), vessel failure and melt ejection modes, the pool can be of different depth and subcooling by the times when the melt release begins and ends [1]. Therefore, in the parametric analysis we assume that the pool depth H_P, pressure in the gas space P_0 and initial subcooling ΔT_{sub} can vary in some ranges chosen from scenario analysis and physical considerations.

2.3. Phenomena Affecting Debris Bed Shape

2.3.1. Particle avalanching

Avalanching of particles is a physical mechanism which limits the slope angle of the debris bed to some maximum value referred to as the angle of repose θ^0_{rep}. If a local slope angle happens to exceed this value, the top layer of particles slides downwards redistributing the material and decreasing thus the slope angle [6]. The main contributors to this physical mechanism are the gravity and drag forces. Of course, avalanching can only be effective provided that no particle sintering, or cake formation occur, which is the case assumed in this study.

The importance of avalanching mechanism from debris bed formation viewpoint is that it establishes the upper limit to the slope angle regardless of the melt release mode and action of other particle spreading mechanisms considered below. Of particular interest there are two cases where this mechanism may affect directly the initial shape of debris bed. One such case is the gradual melt release into a subcooled pool in which no intensive convection occurs until the pool is heated up enough for onset of boiling. The paths of falling melt particles are then not deflected as they travel in the pool, and it is their packing and redistribution by avalanching that determine the shape of growing debris bed on the pool bottom. In the case of a small concentrated particle source and weak particle-flow interaction, this would give a cone-shaped debris bed with the surface slope angle exactly equal to the angle of repose.

Another limiting case is the massive melt release into a deep enough pool, when a coherent melt jet emerges from the failed reactor vessel, fragmenting in the pool into fine particles which rapidly reach the pool bottom. In this case boiling is very intensive, however, the particle-flow interaction time is limited because large mass of corium particles is falling, entraining and evaporating water and, thus, reducing the vertical drag in comparison with falling of individual particles. This case of fuel-coolant interaction was studied mainly from the quenching point of view, but no validated debris bed formation models is available so far. As a conservative assumption, we can also assume that avalanching is the main contributor to particle lateral redistribution in the growing debris bed in this case.

The avalanche model is implemented in DECOSIM in the following way: after each update to debris bed due to falling particles, a condition on the debris bed slope angle is checked, and particles are redistributed to the neighboring cells until the bed surface slope angle is below or equal to the angle of repose θ^0_{rep}. The angle of repose taken in simulations was $\theta^0_{rep} = 35^{\circ}$, which is a typical value for granular materials [6].

2.3.2. Particle spreading by natural convection flows in the saturated pool

Previous DECOSIM simulations have shown that in the case of gradual melt release into a deep saturated water pool the interaction of falling particles with the flow results in spreading of melt over the pool basemat, the smaller the particles and higher the decay heat power, the more effective is the spreading. In order to estimate the efficiency of particle spreading, a simple empirical model can be developed which generalizes the results of simulations [2]. Consider a droplet of diameter d_p falling in the water pool of depth H_P. The terminal velocity of falling droplet V_p is evaluated from the balance of gravity and drag forces:

$$V_p = \left(\frac{4gd_p}{3C_d} \frac{\rho_p - \rho_l}{\rho_l} \right)^{1/2} \tag{1}$$

where the drag coefficient C_d is a function of particle Reynolds number, but for heavy particles it can be assumed that Newton regime is reached in which $C_d \approx 0.45$. The particle-water interaction time in the pool is then proportional to $t_{int} \propto H_P / V_p$. Convection in the pool is governed by vapor release in the debris bed, and the characteristic superficial velocity of vapor on the top surface of debris bed can be evaluated as $V_g = \Gamma \cdot H_b = \rho_p (1-\varepsilon) W H_b / \rho_g \Delta H_{ev}$, where Γ is the volumetric evaporation rate, ε is debris bed porosity, W is the specific decay heat power per unit mass of corium, H_b is the maximum debris bed height, ΔH_{ev} is the latent heat of evaporation. Assuming that characteristic horizontal velocity (responsible for particle spreading) is proportional to V_g, we can write that the characteristic width of debris bed is proportional to $R_b \propto V_g t_{int} \propto \rho_p (1-\varepsilon) W H_b / \rho_g \Delta H_{ev} \cdot (H_P / V_p)$. Therefore, the tangent of slope angle, $\tan\phi \propto H_b / R_b$, is expected to depend on a non-dimensional parameter χ:

$$\tan\phi = f(\chi), \qquad \chi = \frac{\Delta H_{ev} \rho_g}{\rho_p (1-\varepsilon) W H_P} \left(\frac{4gd_p}{3C_d} \frac{\rho_p - \rho_l}{\rho_l} \right)^{1/2} \tag{2}$$

where the vapor density must be evaluated at the pressure near the pool bottom, i.e., with the hydrostatic head taken into account: $\rho_g = \rho_g (P_{sys} + \rho_l g H_P)$, with P_{sys} being the system pressure in the gas space above the pool level.

The tangent of debris bed slope angle $\tan\phi$ must be an increasing function of χ: the higher the value of χ, the weaker the interaction of particles and convective flow. The above formula is qualitatively correct because it predicts <u>more efficient</u> spreading (smaller χ) due to the following factors:

- Lower system pressure: lower vapor density ρ_g means larger vapor volume and more intensive convection in the pool;
- Larger pool depth H_P (vapor density is increasing in the nominator, but the denominator overweighs it, and χ is a decreasing function of H_P);
- Smaller particle diameter d_p;
- Higher specific decay heat power W;

The function $\tan\phi = f(\chi)$ must be obtained from numerical simulations. A tentative form may be proposed as $\tan\phi = A \cdot \chi^B$ satisfying the condition $\tan\phi|_{\chi=0} = 0$ ("infinitely efficient" spreading results in a flat debris bed).

Results of six numerical simulations reported in [2] were processed, each performed for saturated pool of 8 m depth, with the system pressure of 1 bar. The main variable parameters were the decay heat power ($W = 25$ and 62.5 W/kg) and particle size ($d_p = 3$, 5, and 10 mm). For each simulation, the final shape of debris bed was processed, and the characteristic tangent of slope angle determined. The data obtained are presented in Fig. 1 by the points. The solid line shows the best fit to the data, with $A = 0.1076$ and $B = 1.86$. By the horizontal dashed line, the tangent of typical avalanche angle $\theta^0_{rep} = 35^o$ is plotted, indicating that the fit obtained describes the whole interval of interest.

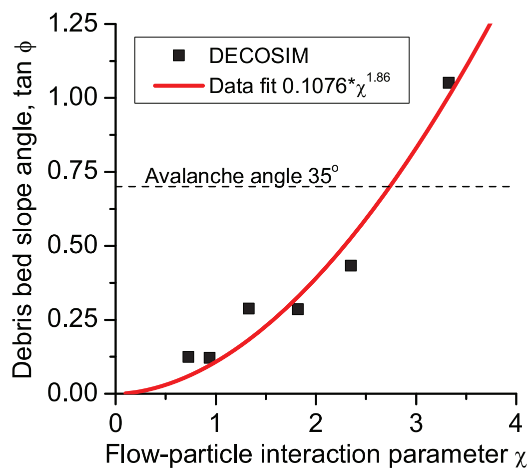


Figure 1. Debris bed slope angle for gradual formation of debris bed in saturated water pool.

Having in hand the approximation (Fig. 1), it is easy to show that for prototypic conditions relevant to severe accidents at Nordic-type BWRs particle spreading in the saturated pool is an effective mechanism for reducing the height of debris bed. Since it takes few hours after SCRAM for reactor pressure vessel to fail and gradual melt release to begin, the decay heat power can be expected to be in the range 100–150 W/kg. The largest mean particle diameter, as is suggested by available melt-coolant interaction experiments, can be expected in the range of 1–5 mm. From the particle spreading point of view, the largest slope angle expected can be about 8 degrees maximum, reached for the largest particle diameter and lowest decay heat power. Smaller particles are distributed almost evenly over the pool basemat. Thus, we can conclude that if the pool is at saturated conditions, particle spreading by natural convection flows is an effective physical mechanism preventing formation of tall debris beds which can prove non-coolable in the case of gradual melt release. Therefore, this case is not considered in the rest of this work.

2.3.3. Particle spreading by natural convection flows in the subcooled pool

If the pool is subcooled, vapor released by the debris bed condenses above it, so that the pool remains single-phase beyond the debris bed for a substantial period (the case of gradual melt release is considered here). Simulations of debris bed formation in a subcooled pool performed in [3] showed that temperature differences arising in the pool cause some natural circulation, but it is much weaker than that in a saturated pool and, therefore, the shape of debris bed at the initial stage is governed by particle avalanching only. However, gradual increase in the pool temperature due to latent and fusion heat transferred from hot melt particles, as well as decay heat released in corium results in boil-up of the pool after some delay time. The boil-up starts at the top layer of the pool where hot water plume from the debris bed reaches saturation conditions, while the rest of the pool remains subcooled. After the onset of boil-up, intensive convection starts in the pool, so that the remaining part of melt interacts with the circulatory flow in the pool and is dispersed efficiently over the pool basemat. Thus the debris bed grows upwards mainly at the pre-boiling stage, while afterwards it mostly grows laterally, with the particle sedimentation flux distributed evenly over the pool bottom. This simple scheme can be used to set up the intermediate or final shape of the debris bed.

The time to boil-up of a pool having initial subcooling $\Delta T_w^0 = T_{sat}^0 - T_w^0$ (T_{sat}^0 is the saturation temperature at the pool pressure, T_w^0 is the initial water temperature) can be evaluated from a simple energy balance model offered in [3]. Consider the total mass of melt M_w supplied to the water pool over the period t_0 (gradual melt release mode). The specific heat (per unit mass of melt) transferred to water is $q = c_{m.l}\left(T_m^0 - T_m^M\right) + \Delta H_f + c_{m,s}\left(T_m^M - T_{sat}^0\right)$, where $c_{m,l}$ and $c_{m,s}$ are specific heat capacities of liquid and solid corium, ΔH_f is the fusion heat, T_m^0 is the initial melt temperature, T_m^M is the melting temperature of corium,. Introduce the non-dimensional time of pool boil-up, $\tau = t_{boil}/t_0$ where t_{boil} is the time after which the pool temperature is increased by ΔT_w^0 and the pool becomes saturated. It is shown in [3] that

$$\tau = \frac{\sqrt{2B\xi + 1} - 1}{\xi}, \qquad B = \frac{M_w c_w \Delta T_w^0}{M_m q}, \qquad \xi = \frac{W t_0}{q} \tag{3}$$

where B is the ratio of energy necessary to bring the pool to saturation and the total latent and fusion energy of melt, ξ is the ratio of decay and latent heats.

If we assume that at the pre-boiling stage the growing debris bed has conical shape with the slope angle equal to the repose angle, then the debris bed height at the time of boil-up is given by

$$H_{DB}(\tau) = \left(\frac{3V_B^{\max}\tan^2\theta_{rep}^0}{\pi}\right)^{1/3}\left(\frac{t}{t_0}\right)^{1/3}, \quad t \le t_{boil} \tag{4}$$

where $V_{DB}^{\max} = M_m/\rho_p(1-\varepsilon)$ is the total volume of porous debris bed. After the boil-up, it can be assumed that the remaining volume of debris, $V_{DB}^{\max}(1-\tau)$, is distributed evenly over the pool bottom, adding to the debris bed a layer of height $4V_{DB}^{\max}(1-\tau)/\pi D_P^2$. This simple geometry approximation is confirmed by numerical simulations at different subcoolings in [3].

2.3.4. Particle spreading due to vapor release in the debris bed

Boiling in the heat-releasing particulate debris bed is the source of mechanical energy which causes partial fluidization of the top layer and lateral redistribution of particles, referred to as "self-leveling" [7, 8]. A scalable empirical closure for the lateral particle flux as a function of local slope angle , particle properties and superficial vapor velocity at the debris bed top (related to the evaporation rate in the debris bed bulk) was developed recently as the generalization of PDS-C experiments [8, 9]. The model is formulated in non-dimensional variables:

$$
\begin{aligned}
&Q_p^* = \frac{Q_p}{\rho_p (\sigma/\mu_l) d_p} = F\left(Q_g, \mathrm{Ar}_{lg}, \gamma, \Phi\right) \\
&Q_g = \frac{U_g}{U_{mf}}, \quad \mathrm{Ar}_{lg} = \frac{\rho_g \left(\rho_p - \rho_l\right) g d_p^3}{\mu_g^2}, \quad \gamma = \frac{\tan\theta_{rep}(Q_g)}{\tan\theta_{rep}^0}, \quad \Phi = \frac{\tan\phi}{\tan\theta_{rep}(Q_g)}
\end{aligned}
\tag{5}
$$

Here, Q_p^* is the normalized particle flux, $Q_g = V_g / V_{mf}$ is the non-dimensional gas injection velocity defined as the ratio of the superficial gas velocity at the debris bed top and the minimum fluidization velocity $V_{mf} = \mu_g \mathrm{Re}_{gmf} / \rho_g d_p$, with the Reynolds number $\mathrm{Re}_{gmf} = \left(33.7 + 0.0408 \cdot \mathrm{Ar}_{lg}\right)^{1/2} - 33.7$ defined in terms of the gas phase Archimedes' number Ar_{lg} [10]. In (5), ρ_i and μ_i are densities and viscosities of respective phases (subscripts p, l, and g refer to particles, liquid and gas phases), σ is the surface tension, d_p is the equivolume sphere diameter. The two rightmost arguments in the function for Q_p^* are the normalized repose angle $\theta_{rep}(Q_g)$ (with θ_{rep}^0 being the repose angle at zero gas velocity) and normalized slope angle ϕ. The repose angle $\theta_{rep}(Q_g)$ at a given gas velocity is approximated by

$$
\theta_{rep}(Q_g) = \theta_{rep}^0 - \sin^{-1}\left(\frac{C_d(\mathrm{Re}_g) V_g |V_g|}{C_d(\mathrm{Re}_{gmf}) V_{mf} V_{mf}} \sin\theta_{rep}^0 \right) \tag{6}
$$

where $C_d(\mathrm{Re}) = (24/\mathrm{Re})\left(1 + C_1 \mathrm{Re}^{C_2}\right) + C_3 \mathrm{Re}/(\mathrm{Re} + C_4)$ is the drag coefficient, $C_1 - C_4$ depend on particle sphericity S: $C_1 = 8.1716 \exp(-4.0655 \cdot S)$, $C_2 = 0.0964 + 0.5565 \cdot S$, $C_3 = 73.69 \exp(-5.0748 \cdot S)$, $C_4 = 5.378 \exp(6.2122 \cdot S)$ [11]. In (6), the Reynolds number in the nominator, $\mathrm{Re}_g = \rho_g V_g d_p / \mu_g$, is based on the actual gas velocity V_g, while that in the denominator is based on the minimum fluidization velocity V_{mf} defined above. Particle sphericity $S \le 1$ is the ratio of the surface area of a sphere with the same volume as the particle, to the actual surface area of the particle.

The functional dependence of non-dimensional particle flux $Q_p^* = F\left(Q_g, \mathrm{Ar}_{lg}, \gamma, \Phi\right)$ was obtained by the regression analysis of the data obtained in PDS-C experiments [8–9]:

$$
Q_p^* = K \cdot Q_g^a \cdot \mathrm{Ar}_{lg}^b \cdot \gamma^c \cdot \Phi^d \tag{7}
$$

where for $Q_p^* \ge 2.31 \cdot 10^{-4}$ the constants are $K = 0.182$, $a = 0.408$, $b = -0.495$, $c = 2.593$, $d = 3.848$, whereas for $Q_p^* < 2.31 \cdot 10^{-4}$ the best fit is achieved for $K = 0.0042$, $a = 0.746$, $b = -0.195$, $c = 0.879$, $d = 2.738$.

The model (1)–(3) was implemented in DECOSIM in order to simulate particle redistribution due to "self-leveling" in the course of debris bed formation or further cooling. The model uses the gas flux provided by the porous media coolability solver and is applicable for both saturated and subcooled pool conditions. As the input parameters, the repose angle at zero gas velocity, θ_{rep}^{0}, and particle sphericity, S, are used. The particle flux is evaluated from equations (1)–(3), with the superficial gas velocity V_g obtained from the solution of two-phase equations describing two-phase flow in the debris bed. In this respect, interaction of the two-phase flow with debris bed shape change is captured in the fully coupled manner. Note that in [12] a simplified treatment of gas velocity is adopted, with the superficial gas velocity evaluated as $V_g = \rho_p (1-\varepsilon) Wh / \rho_g \Delta H_{ev}$, where ε is debris bed porosity, W is the specific decay heat power per unit mass of corium, h is the local debris bed height, ΔH_{ev} is the latent heat of evaporation. Such a model allows one to perform simulations without the need of solving complex two-phase equations, however, its validity must be established by comparison with the fully coupled simulations.

3. RESULTS

3.1. Parameters

The above discussion of physical mechanisms affecting the formation and ultimate shape of debris bed in different scenarios shows that if melt release occurs gradually, and the pool is close to saturation, particles are dispersed effectively over the pool basemat, so that a nearly flat debris bed can be expected, the smaller the particles, the lower the debris bed height. From the coolability point of view, the most dangerous configuration is exactly the opposite one, when the debris bed is tall and consists of small particles. Such a configuration can be expected if the pool is subcooled, or if the melt is released rapidly and the interaction time of particles and flow is limited. In both cases a conservative assumption is that the initial debris bed shape corresponds to a cone with the initial slope angle close to the angle of repose θ_{rep}^{0}. In what follows, we demonstrate results of coupled two-phase flow and particle spreading simulations starting with this initial configuration.

In order to evaluate possible effect of particle spreading on debris bed shape and coolability, a set of simulations was performed

- Initial debris bed height: 2 m;
- Slope angle equal to avalanche angle of 30 degrees;
- Particle size: 1, 1.5 and 2 mm;
- Relocation time: 1.5 and 3 hours (used to evaluate the decay heat power according to ANS5.1 standard curve);
- Transient duration: 2 hours.

The results of DECOSIM predictions for debris bed height are compared with those obtained from a simple model in which the superficial gas velocity is evaluated from the heat released in the debris layer of local debris bed height [12]. Also, post-dryout stage is considered at which the maximum temperatures reached in the debris bed are compared with those calculated without particle spreading taken into account (fixed-shaped debris bed).

3.2. Summary of Simulations

In Table I, all simulation cases are presented, with their outcomes indicated. Generally, three main outcomes were observed: i) a coolable debris bed without dryout occurrence; ii) dryout in the top part of debris bed persisting for some time, followed by reflooding and quenching of the dry zone, and iii) dryout with steady temperature escalation. All these cases are discussed in detail from the debris bed shape and coolability points of view in the following two sections.

Table I. Simulations of debris bed self-leveling and coolability

Particle diameter d_p, [m]	Relocation time t_r, [hours]	Bed height after 1 h (DECOSIM)	Bed height after 1 h (Model [12])	Coolability
1.0	1.5	1.55	1.63	Dryout
	3.0	1.55	1.66	Dryout
1.5	1.5	1.61	1.67	Dryout/Reflooding
	3.0	1.67	1.70	Dryout/Reflooding
2.0	1.5	1.65	1.68	No Dryout

3.2. Particle Spreading Effect on Debris Bed Shape

Consider first the change in debris bed shape due to particle spreading (self-leveling mechanism). In Fig. 2, the time histories of debris bed height $H_{DB}(t)$ are presented for particle diameters $d_p = 1$ mm (*a*), 1.5 mm (*b*), and 2 mm (*c*).

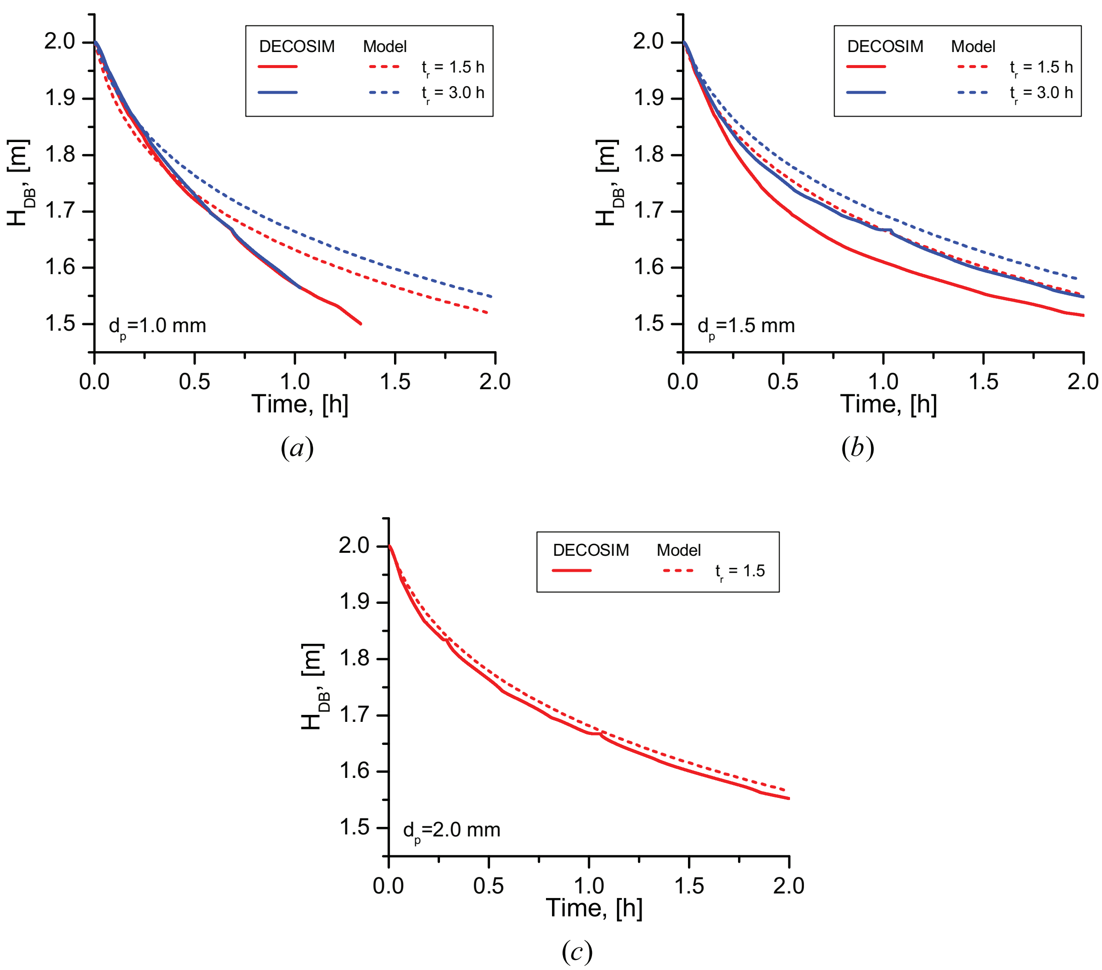


Figure 2. Debris bed heights vs time for different particle diameters and relocation times: DECOSIM simulations compared with simple model [12].

Figure 2,*c* shows the results corresponding to large particles for which the debris bed is coolable (see Table I). One can see that the solid curve (DECOSIM simulation) agrees well with the dashed curve obtained by the simplified model [12]. This can be considered as verification of the numerical implementation of particle spreading model in DECOSIM (see Section 2.3.4). At the same time, it confirms that for a coolable debris bed the vapor velocity is directed vertically, and the simplified model for the gas velocity at the debris bed top gives quite good accuracy. Some discrepancy between the curves in Fig. 2, *c* is observed at the initial stage, but it is related to mesh effects which are noticeable as long as the tip of conical debris bed remains acute; after it is flattened out, both curves remain parallel, which confirms that the spreading rate is the same in the full and simplified models.

Figures 2*a*, *b* correspond to the cases where dryout occurred in the debris bed (see Table I). One could argue that dryout might deteriorate particle spreading because there is no evaporation in the dry zone, and the superficial gas velocity might be reduced above the dry zone. However, numerical results presented in Fig. 2*a*, *b* show that particle spreading is becoming even more effective in comparison with the no-dryout conditions (represented by the curves obtained from the model [12]). This phenomenon can be explained by gas heating in the dry zone which reduces the vapor density and, therefore, increases the superficial velocity. Another reason could be attributed to “focusing” of vapor flow towards the dry zone due to higher gas buoyancy in the single-phase dry zone in comparison with the two-phase mixture in a “wet” debris bed.

The latter finding is important because it shows that the model [12] gives a conservative estimate for debris bed shape and its effect on coolability (i.e., in the case of dryout occurrence it predicts slower self-leveling of debris bed than the full model). Due to its simplicity, the model [12] can be used in the context of sensitivity and uncertainty studies, or can be used as a surrogate model for debris bed shape for extensive sensitivity and uncertainty analysis in safety assessment.

3.3. Particle Spreading Effect on Debris Bed Coolability

Figure 3 summarizes the predicted time histories of solid particle maximum temperatures in the simulations where dryout occurred (simulations with particle diameter of 2 mm resulted in no dryout, therefore, temperatures were near the saturation point and are not shown due to triviality). One can see that debris beds with 1 mm particles are non-coolable, regardless of whether particle spreading is taken into account or not; these are featured by steady temperature escalation.

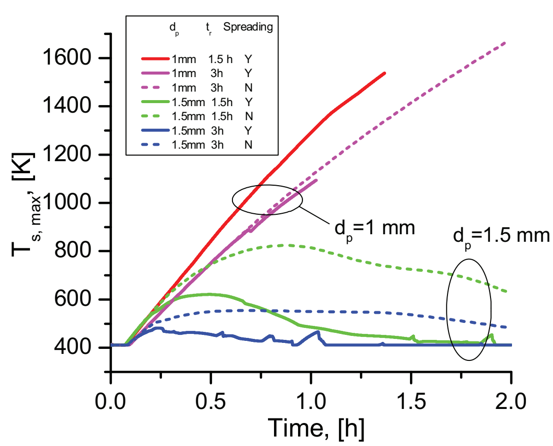
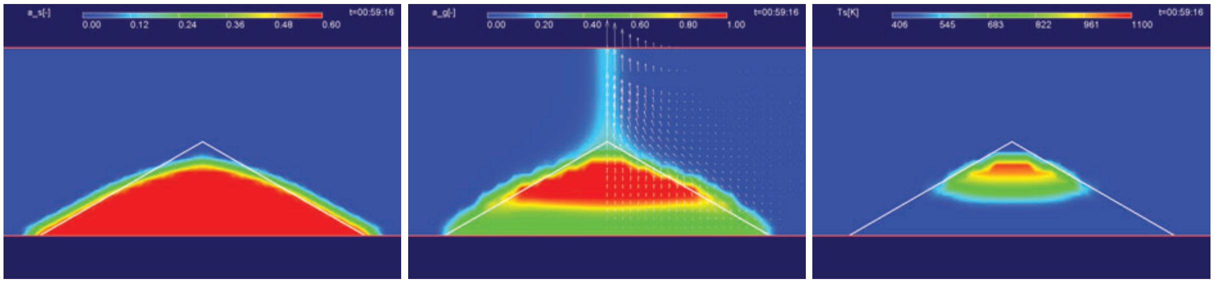
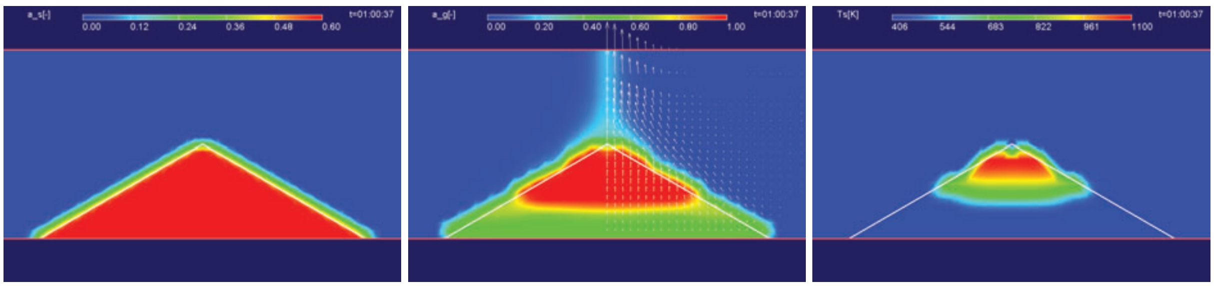


Figure 3. Maximum temperatures of solid particles in simulations with (Y) and without (N) particle spreading.

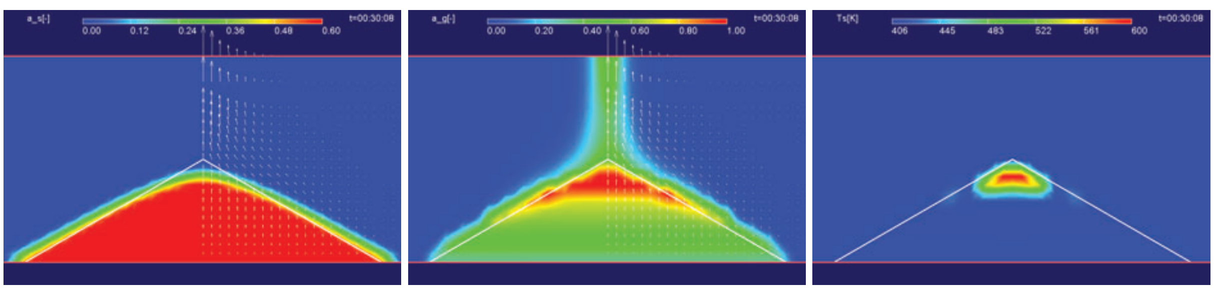


With particle spreading

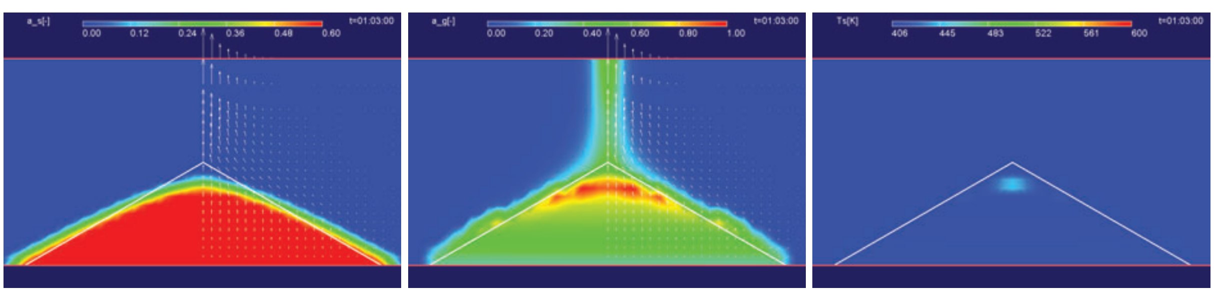


Without particle spreading

Figure 4. Volume fraction of particles (left), void fraction (middle) and particle temperature (right) in the debris bed with 1 mm particles at time 1h after relocation.



Time: 30 min



Time: 1 h

Figure 5. Volume fraction of particles (left), void fraction (middle) and particle temperature (right) in the debris bed with 1.5 mm particles at times 30 min (top row) and 1h (bottom row) after relocation.

On the other hand, debris beds with particle diameter of 1.5 mm are featured by dryout, however, temperature is stabilized due to vapor cooling, and even in the case of fixed-shape debris bed it gradually decreases due to decrease in the decay heat power with time. If particle spreading is active, slumping of the debris bed results in its faster reflooding (compare the solid lines with corresponding dashed lines in Fig. 3).

In Fig. 4, the case of debris bed with 1 mm particles is demonstrated (the initial shape of debris bed is shown by white lines). The relocation time for this case was $t_r = 3$ h, the distributions are shown at time 1 h after relocation, i.e., 4 h after SCRAM. One can see that significant part of debris bed (roughly, upper half of its height) is dry; slumping of the debris bed due to particle spreading reduces somewhat the size of high-temperature zone, but effect of the slumping is insufficient to prevent material reheating.

In Fig. 5, the case where debris bed reflooding occurs is presented (particle diameter 1.5 mm, relocation time $t_r = 1.5$ h, the distributions are shown at times 30 min and 1 h after relocation, i.e., 2 and 2.5 h after SCRAM). The dry zone is limited in size, the temperature in the dry zone is stabilized by vapor flow and then returns to saturation as material rewetting proceeds due to combined effect of debris bed slumping and gradual decrease in the decay heat power.

4. CONCLUSIONS

The physical mechanisms considered in this paper decrease the possibility that a tall non-coolable ex-vessel debris bed can be formed in the course of severe accident where deep enough water pool is available. Among the important findings of this work is the development of a correlation for particle spreading in a saturated water pool, and demonstration that self-leveling of debris bed is not deteriorated if dryout occurs in the bed. Taking into account these mechanisms will be important in safety and risk analysis because they change the failure domain related to ex-vessel debris bed coolability.

These mechanisms, though, have their own efficiency limits which have to be taken into consideration. For example, particle spreading in the pool due to natural circulation flows only becomes efficient after boil-up of water (even partial), therefore, some delay is expected if water subcooling is high. Particle spreading due to partial fluidization of the top layer of the debris bed (self-leveling) possesses its own time scales and may be insufficient for temperature stabilization, even though debris bed slumping proceeds. Also, if the pool depth is smaller than the melt jet breakup length, a solidified "cake" can be formed in the top part of debris bed. In this latter case, evidently, the particle spreading mechanism discussed in the paper is not effective. Debris agglomeration is not only a problem for spreading, but it also significantly deteriorate debris bed coolability due to increased resistance for the coolant flow through the porous media [13]. Therefore, further comprehensive research is necessary in order to put these phenomena in the time frame of severe accident scenarios.

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