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Effectiveness of the debris bed self-leveling under severe accident conditions

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ABSTRACT

Melt fragmentation, quenching and long term coolability in a deep pool of water under the reactor vessel are employed as a severe accident mitigation strategy in several designs of light water reactors. The success of such strategy is contingent upon the natural circulation effectiveness in removing the decay heat generated in the porous debris bed. The maximum height of the bed is one of the important factors which affect the debris coolability. The two-phase flow within the bed generates mechanical energy which can change the geometry of the debris bed by the "self-leveling" phenomenon. In this work we developed an approach to modeling of the self-leveling phenomenon. Sensitivity analysis was carried out to rank the importance of the model uncertainties and uncertain input parameters i.e. the conditions of the accident scenario and the debris bed properties. The results provided some useful insights for further improvement of the model and reduction of the output uncertainties through separate-effect experimental studies. Finally, we assessed the self-leveling effectiveness, quantified its uncertainties in prototypic severe accident conditions and demonstrated that the effect of self-leveling phenomenon is robust with respect to the considered input uncertainties.

1. Introduction

The containment is the last barrier protecting against the release of fission products into the environment in a hypothetical severe accident (SA) with a corium melt release from the reactor pressure vessel (RPV). Nordic type boiling water reactors (BWRs) adopt the flooding of the lower drywell as a SA management strategy. The termination of the ex-vessel accident progression should be achieved by fragmenting and quenching of the molten core materials in a 7–12 m deep water pool under the reactor vessel. The decay heat should be removed from the porous debris bed by natural circulation of the coolant. The success in cooling the debris bed depends mainly on the:

1. properties of the bed (e.g. particle size, porosity and shape of the debris bed);
2. accident scenario conditions (e.g. decay heat, system pressure).

A tall bed is hardly coolable since it is most prone to dryout (Yakush et al., 2012). As pointed by Yakush et al. (2012) the same mass of debris may or may not be coolable depending on the maximum height of the bed. Therefore physical phenomena that can influence the shape of the debris bed and reduce its maximum height are of safety importance and should be addressed in a safety analysis. Two distinct phenomena can promote the debris spreading along the containment basemat: (i) spreading of particles in the pool and (ii) debris bed self-leveling after debris bed packing. The phenomenon of particles spreading during sedimentation in a prototypic size pool was first investigated theoretically by Yakush and Kudinov (2009) and Yakush et al. (2009) for a gradual release (i.e. in a dripping mode) of corium. It was shown that large scale natural circulation currents induced by the decay heat can effectively spread prototypic size particles over the basemat. Later in Yakush and Kudinov (2011) it was demonstrated that, in case of initially subcooled pool, the spreading becomes effective only after onset of boiling in the pool volume. Currently, experimental research (Kim et al., 2014; Konovalenko et al., 2016) is ongoing to provide data for validation of the complex three-phase flow codes used for modeling of this phenomenon.

Depending on the accident scenario (e.g. initial pool subcooling, amount of debris, decay heat, melt release conditions etc.) the initial shape of the bed can be affected by particles spreading in the pool. Once the debris bed is packed its shape can still change by so called self-leveling phenomenon. Such phenomenon is driven by the steam generated in the process of the decay heat removal.

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Nomenclature

Roman letters

$a \cdot 100$	probability of the output distribution [%]
a_{cl}	coefficient of the closure uncertainty [–]
Ar_{lg}	gas phase Archimedes number with liquid-buoyed solids [–]
$b \cdot 100$	confidence level [%]
b_{cl}	coefficient of the closure uncertainty [–]
C_d	drag coefficient [–]
D	tridiagonal matrix used in the implicit integration scheme [–]
d_p	effective particle diameter [mm]
EE	elementary effect [m]
f	element of the matrix D [–]
g	gravity acceleration [m/s^2]
h	height [m]
H_e	latent heat of water evaporation [kJ/kg]
k	number of input parameters in the extended Morris method [–]
k_{cl}	closure uncertainty [–]
L	width of the considered cell [m]
m	mass [kg]
M_o	maximum corium mass [kg]
N	total number of model evaluations [–]
p_r	relative power [%]
q	element of the matrix D [–]
Q_{HF}	heat flux [W/m^2]
Q_p	particle mass flow per unit width [kg/(m $\cdot$ s)]
Q_p^*	normalized particle flow rate [–]
r	radial distance [m]
R	number of trajectories in the extended Morris method [–]
Re	Reynolds number [–]
Re_{gmf}	gas Reynolds number at minimum 3-phase fluidization [–]
RP	reactor thermal power [GW]
t_{oper}	reactor operation time [days]
t_{scram}	elapsed time since scram [h]
t_r	relocation time after scram [h]
u_g	normalized gas velocity [–]
U_{mf}	superficial gas velocity at minimum 3-phase fluidization [m/s]
U_g	superficial gas velocity [m/s]
W_{decay}	specific power of decay heat [W/kg]
x	planar or radial coordinate [m]

Greek letters

β	non-dimensional term in the universal expression for closure [–]
γ	non-dimensional term in the universal expression for closure [–]
ε	bed porosity [–]
θ_p	slope angle [°]
θ_{rep}	critical angle of repose [°]
μ	mean of elementary effects [m]
μ^*	modified mean of elementary effects [m]
μ_g	gas viscosity [Pa s]
μ_l	liquid viscosity [Pa s]
ξ	small number [–]
ρ_b	bulk density of debris bed [kg/m^3]
ρ_g	gas density [kg/m^3]
ρ_l	liquid density [kg/m^3]
ρ_{st}	steam density [kg/m^3]
ρ_p	particle density [kg/m^3]
σ	surface tension [N/m]
σ_{EE}	standard deviation of elementary effects [m]

Escaping from the porous bed, such steam flow is a source of mechanical energy, which can move the debris particles residing at the bed's top layer and can lead to leveling the debris bed (Zhang et al., 2010). Spreading phenomena are effective in promoting the debris coolability if the time scale for reaching a coolable configuration is smaller than the time scale for drying out and onset of re-melting of the debris. In this work the effect of the self-leveling was studied in detail and, as a conservative approach, the initial debris bed shape was assumed to be conical with the slope angle equal to the repose angle (i.e. particles spreading induced by the large turbulent currents was assumed to be ineffective).

The self-leveling phenomenon was studied experimentally in the past, mostly motivated by the debris coolability in core-disruptive accidents in sodium-cooled fast reactors. The first experimental studies carried out by Hesson et al. (1971), Gabor (1974) and Alvarez and Amblard (1982) confirmed the existence of the particulate spreading phenomenon due to the gas flow through the bed. Some further investigations (Basso et al., 2016, 2014; Cheng et al., 2014, 2013, 2011; Konovalenko et al., 2012; Zhang et al., 2011, 2010) demonstrated that the time scale for the self-leveling process can significantly vary, depending on the initial debris bed configuration, particles properties and gas velocity. A depressurized water boiling technique was used by Zhang et al. (2011) to study the influence of parameters as particle size, density, etc. However, the effective steam generation rate in the tests was almost two orders of magnitude smaller than in prototypic accident conditions and most of the tests were carried out with low density particles. Cheng et al. (2014, 2013, 2011) carried out a series of experiments with nitrogen percolation in order to achieve more prototypical gas superficial velocities. An empirical correlation for the ratio of the instantaneous slope angle of a conical heap to the initial angle was proposed. However, no method was introduced to generalize and extrapolate the empirical data, obtained in the laboratory scale tests with particles of different materials and regular shapes, to the prototypic accident conditions.

Experimental results obtained in the PDS-C facility (Basso et al., 2016, 2014; Konovalenko et al., 2012) suggested that the particles motion induced by the local gas-coolant-particle interactions occurs only in a thin top layer of the bed. These observations confirmed that experiments carried out in reduced laboratory scale can capture the key physical processes responsible for the debris self-leveling as long as the size of the facility is much larger than the characteristic size of the moving particles. A scaling approach and a universal non-dimensional empirical closure for particle mass flow rate per unit width were proposed and validated against the experimental data obtained with different particles and various gas superficial velocities (Basso et al., 2016, 2014). Scalability is important for modeling of the effectiveness of the particulate debris spreading (PDS) at reactor scale.

An approach to predict the spreading dynamic of a planar debris bed was proposed in Konovalenko et al. (2012). Such approach was based on solving the mass-balance equation for the debris bed using experimentally obtained closures for the particle mass flow rate per unit width at the bed top surface.