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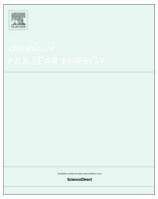

Numerical investigation on quench of an ex-vessel debris bed at prototypical scale

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ABSTRACT

This paper is concerned with the coolability of the heap-like debris beds formed in the cavity of a Nordic-type boiling water reactor (BWR) during a postulated severe accident. A numerical simulation using the MEWA code was performed to investigate the quenching process of the ex-vessel debris bed at post-dryout condition upon its formation. To qualify the simulation tool, the MEWA code was first employed to calculate the quenching tests recently conducted on the PEARL facility. Comparisons of the simulation results with the experimental measurements show a satisfactory agreement. The simulation for the debris bed of the reactor scale shows that the heap-like debris bed flooded from the top is quenched in a multi-dimensional manner. The upper region adjacent to the centerline of the bed is the most difficult for water to reach under the top-flooding condition, and thus is subject to a higher risk of remelting. The oxidation of the residual Zr in the corium has a great impact on the coolability of the debris bed due to (i) large amount of reaction heat and the subsequent positive temperature feedback, (ii) the local accumulation of the produced H_2 which may create a "steam starvation" condition and suppresses the oxidation. As possible mitigation measures of oxidation, the effects of bottom-flooding and bypass on quench were also investigated. It is predicted that the debris bed becomes more quenchable with water injected from the bottom, especially for the case with the floor partially flooded in the center. A bypass channel embedded in the center of the debris bed can also promote the quenching process by providing a preferential path for both steam escape and water inflow.

1. Introduction

In the event of a severe accident in a light water reactor (LWR), degradation of fuel rods and collapse of internal structures due to rapid core heat-up lead to relocation of core melt (corium). The corium may accumulate in either the lower plenum of the reactor pressure vessel (RPV), or in the reactor cavity if the vessel wall is breached. The in-vessel debris bed may form as a result of reflooding of the core, which is employed as a severe accident management strategy by some LWRs' design. While for the case of a Nordic boiling water reactor (BWR), whose reactor cavity is filled with deep water, the jet of molten corium discharged from vessel will fragment into small particles, and subsequently form a porous ex-vessel debris bed after sedimentation. The residual decay heat inside the debris bed must be continuously removed by coolant in order to stabilize and terminate the accident progression; otherwise a large molten pool may form and expand which will eventually threat the integrity of the RPV or containment.

To assess the coolability of the debris bed, the dryout heat flux (DHF), i.e. the maximum heat flux prior to the dryout, is usually considered as the limiting criterion for heat removal capacity. It has been extensively investigated in many experiments, coolability analyses and numerical simulations, with a quasi-steady assumption that the debris bed is already in thermal equilibrium with the covering saturated water (Lindholm et al., 2006; Thakre et al., 2014; Takasuo, 2016; Lipinski, 1982). However, the DHF is concerned with the long-term coolability of a debris bed. Whereas the more realistic scenario is that the hot molten corium is initially dry and first needs to go through a quenching process, where the local thermal-equilibrium may no longer be valid everywhere. As observed in the DEFOR-E experiment (Karbojian et al., 2009), the temperature of the debris bed from melt coolant interaction still remained higher than the saturation temperature of water for more than 100 s after settling down to the bottom of water pool, far behind the melt-coolant-interaction time of 10 s. In reactor situation with decay heat, such "dry zone" of debris bed will continue to heat up before the arrival of quench front due to the insufficient cooling capacity, and consequently starts remelting if the temperature exceeds the solidus temperature. Therefore, the assessment

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Nomenclature

A	pre-exponential factor in the Arrhenius equation (cm^2/s or $(g/cm^2)^2/s$)
B	activation energy in the Arrhenius equation (J/mol)
c_p	specific heat capacity at constant pressure [J/(kg·K)]
d	particle diameter (m)
F_{pg}	volumetric frictional drag force between solid particle and vapor (N/m^3)
F_{pl}	volumetric frictional drag force between solid particle and liquid (N/m^3)
F_i	volumetric interfacial drag force between liquid and vapor (N/m^3)
g	gravitational acceleration constant (m/s^2)
h	heat transfer coefficient [$W/(m^2 \cdot K)$]
i	specific enthalpy (J/kg)
j	superficial velocity (m/s)
j_r	relative velocity (m/s)
Ja	Jakob number (–)
k	conductivity [W/(m·K)]
K	permeability (m^2)
K_{oxi}	kinetic constant of the oxidation (cm^2/s or $(g/cm^2)^2/s$)
K_r	relative permeability (–)
Nu	Nusselt number (–)
p	pressure (Pa)
Pr	Prandtl number (–)
Q	volumetric heat (W/m^3)
R	gas constant [J/(mol·K)]
r	radius (m)
Re	Reynold number (–)
$s = 1 - \alpha$	saturation (–)
T	temperature (K)
t	time (s)
V	velocity (m/s)
X	layer thickness (cm) or oxygen mass per unit area (g/cm^2)

Greek letters

α	void fraction (–)
Γ	evaporation rate [$kg/(m^3 \cdot s)$]
ε	porosity (–)
η	passability (m)
η_r	relative passability (–)
θ	contact angle (rad)
μ	dynamic viscosity [kg/(m·s)]
ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscripts

c	capillary
i	interface
l	liquid
g	gas, steam
p	solid particle
q	the qth phase of fluid (liquid or gas)
sat	saturated
r	relative

Superscripts

FB	film boiling
in	injection
max	maximum
min	minimum
NB	nucleate boiling
oxi	oxidation

of the probability of the successful quenching of a hot debris bed is also important and necessary since it is the prerequisite for achieving long-term coolability of debris bed.

In the quenching process, the temperature difference between solid particles and fluid (steam and liquid water) is large, and the flow patterns and heat transfer mechanisms are complex, making it difficult for experimental measurement and modeling. Several experiments have been carried out to study the quenching of initially hot and dry debris bed by flooding from either top or bottom. Tutu et al. (1984) quenched the debris bed by the saturated water injected from the bottom with constant flow rates. The experimental results exhibited that the quench front propagates in a one-dimensional frontal manner at an approximately constant speed for small liquid supply rate, and demonstrated the necessity of developing a more reliable model to predict the solid-fluid heat transfer coefficient. While the bottom-quenching of a homogeneous debris bed usually proceeds with a uniform one-dimensional front, flooding from the top is more complex, characterized by a multi-dimensional progression. Ginsberg et al. (1986) found that the top-quenching is a two-stage process, which consists of an initial downward penetration followed by an upward filling process after the downward flow reaches the bottom. The top-quenching tests for a debris bed in a crucible conducted on the DEBRIS facility (Schäfer et al., 2006; Leininger et al., 2014) also showed a similar process. Furthermore, it was also observed that the water preferably penetrated along the crucible wall during the downwards stage, which can be attributed to the lower temperature and higher porosity (wall effect) in this peripheral region. This is also confirmed by Tung and Dhir (1987), who performed a series of tests using both vertically and radially stratified porous beds to simulate more prototypical conditions. In contrast, Cho and Bova (1982) reported an opposite observation, i.e. the injecting water flew faster in the middle part of debris bed during top-flooding process. One of the recent quenching experiments was carried out on the PRELUDE facility constructed by IRSN, which is the preliminary small test facility of the experimental program PEARL (Repetto et al., 2013).

A few analytic models have been proposed based on the experimental observations and simplified assumptions (Tutu et al., 1984; Tung and Dhir, 1987; Petit et al., 1999; Chikhi and Fichot, 2017). Since these models are only one-dimensional, their applicability is quite limited when confronted with the complexity of the quenching process. Some computational codes have been developed with the capability of simulating the thermal-hydraulics of debris bed during transient quenching process, e.g. ICARE/CATHARE (Fichot et al., 2006), MEWA (previously named WABE, Bürger et al., 2006), MC3D (Raverdy et al., 2017), SCDAP/RELAP5 (Siefken et al., 1999). Corresponding validation works of these simulation tools have also been comprehensively performed against the measurements of quenching experiments performed under various conditions (Raverdy et al., 2017; Bürger et al., 2006; Rahman, 2013; Schäfer et al., 2006; Starflinger et al., 2015; Chikhi et al., 2017). In general, the agreements between the predicted and experimental results are satisfactory, but it is also noted