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Analysis of composition and temperature of debris bed based on settling characteristics of relocated core debris in pool type SFR

S. Muthu Saravanan, Dijo K. David, P. Mangarjuna Rao *, B.K. Nashine, P. Selvaraj

Computational Simulation Section, Safety Engineering Division, Fast Reactor Technology Group, Indira Gandhi Centre for Atomic Research, Kalpakkam, 603 102, India

HIGHLIGHTS

- Analyzed the settling characteristics of UO_2 and SS debris in sodium pool under core relocation scenario in SFR.
- Evaluated the composition profile of bed formed due to settling of core materials debris on in-vessel core catcher.
- Distinct three layer debris bed composition profile is predicted for different size ratios of UO_2 and SS particle mixtures.
- Quenching and solidification of settling debris is analyzed to evaluate their temperature while reaching the core catcher.
- Predicted debris bed initial temperature is very near to lower pool sodium temperature even with conservative assumptions.
- Predicted results of composition profile and bed initial temperature are useful in SFR's PAHR analysis.

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ABSTRACT

The hypothetical core meltdown accident in sodium cooled fast reactors (SFR) is a severe accident situation during which the energetic dispersion of core materials and their relocation may pose a threat to the integrity of reactor containment. During core meltdown accident, part of the molten core materials relocated downwards would be fragmented in the lower plenum sodium pool and settle over the in-vessel core catcher plate and forms a particulate debris bed. The recriticality potential and coolability of the debris bed are strongly influenced by the composition of fragmented particles of different core materials and their size distribution. In this paper, simplified models have been developed to evaluate the incipient conditions i.e., composition profile and initial temperature of the particulate debris bed formed over an in-vessel core catcher plate following the core meltdown accident in pool type SFR. The particle mixture settling process subsequent to the fragmentation of molten core materials in sodium pool has been analyzed to evaluate the composition profile of the debris bed. A 1-D model for particle motion through the stagnant fluid under the influence of gravity has been considered to evaluate the settling characteristics of core materials debris (mainly UO_2 and stainless steel) in liquid sodium for a wide range of possible sizes. By extending this model, the differential settling behaviour of mixture of UO_2 and stainless steel particles in liquid sodium pool has been investigated. The composition profile of the debris bed along its thickness has been evaluated for the material relocation scenario considered with various mass ratios of stainless steel and UO_2 mixture using the published experimental results based particle size distributions. Further, a 1-D transient conduction model is implemented to estimate the temperature of debris particles when they settle on the core catcher plate. Simulations revealed that the particles will be quenched to near the temperature of the liquid sodium in lower pool while reaching the core catcher. The results are useful in assessing the coolability characteristics of debris bed formed on the core catcher and its recriticality potential in the analysis of the Post Accident Heat Removal.

1. Introduction

Core meltdown accident in sodium cooled fast reactors (SFR) is a severe accident situation, which may occur in the unlikely scenario in which there is a serious mismatch between the heat generation and heat removal rates within the core. The extent of core meltdown depends on the type of initiating event and its

* Corresponding author at: Safety Engineering Division, Indira Gandhi Centre for Atomic Research, Department of Atomic Energy, Room No. 315, SRL Building, Kalpakkam, Tamil Nadu 603102, India.

E-mail addresses: mangarjun@gmail.com, pmr@igcar.gov.in (P. Mangarjuna Rao).

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Nomenclature

A_p	Projected area of particle (m^2)
A_s	Surface area of the particle (m^2)
Bi	Biot number
C_d	Drag coefficient
C	Specific heat capacity (J/kg K)
D_p	Particle diameter (m)
D_m	Mass mean diameter (m)
F_d	Drag force $\left(\frac{C_d v^2 \rho A_p}{2}\right)$ (N)
F_b	Buoyancy force $\left(\frac{m\rho g}{\rho_p}\right)$ (N)
F_g	Gravitational force (mg) (N)
H	Enthalpy (J)
h	Sensible enthalpy (J/kg)
h_{tc}	Heat transfer coefficient (W/m^2K)
K	Parameter used for predicting particle settling regime
k	Thermal conductivity (W/m k)
L	Latent heat (J/kg)
m	Mass (kg)
P_{decay}	Decay heat generation rate (W/m^3)
P_i	Decay heat generation rate immediately after reactor shutdown (W/m^3)
q'''	Volumetric heat generation rate (W/m^3)
Re_p	Particle Reynolds number
Ste	Stefan number
T	Temperature (K)
T_i	Initial temperature (K)
T_{Na}	Sodium pool temperature (K)
$T_{solidus}$	Solidus temperature of molten material
$T_{liquidus}$	Liquidus temperature of molten material
t	Time (s)
t_{total}	Total solidification time (s)
v	Velocity (m/s)
v_t	Terminal settling velocity (m/s)
g	Acceleration due to gravity (9.81 m/s^2)

Greek symbols

ρ	Density (kg/m^3)
ρ_p	Particle density (kg/m^3)
μ	Kinematic viscosity (Pa-s)
σ	Standard deviation
β	Liquid fraction
ΔH	Latent heat content (J/kg)

Subscripts

c	Critical
i	Initial
Na	Sodium
p	Particle

progression, and in general melting of the complete core is postulated under extremely unlikely initiating events such as Unprotected Loss Of Coolant Flow Accident (ULOFA) caused by the loss of power supply to coolant pumps accompanied with simultaneous failure of all the shutdown systems.

The ULOFA is a severe most accident condition which envelops the consequences of other postulated events such as propagation of fuel assembly flow blockage without SCRAM, Transient Over Power Accident (TOPA) due to passage of a large gas bubble through core without SCRAM and other less severe transients (Waltar and Reynolds, 1981; Fauske et al., 2002; Chellapandi et al., 2010). The core meltdown accidents in SFR are considered as low probability events because of highly reliable shut down and decay heat removal systems (Chetal et al., 2006). Nevertheless, these scenarios are considered hypothetically in order to ensure the integrity of the reactor primary containment which can significantly reduce radiological hazard potential by retaining the radioactive coolant and molten fuel debris released from the core following the accident (Marchaterre, 1977; Gluekler et al., 1977; Peak et al., 1977). The inclusion of an in-vessel core catcher plate in SFR main vessel is a noteworthy design feature to reduce the damage potential of core meltdown accidents. The core catcher plate enables the adequate cooling of fuel debris relocated downwards and also reduces the chances of recriticality by avoiding the lumping of fuel debris at the bottom of main vessel.

During a core meltdown accident, part of the molten core materials (Mixed Oxide fuel ($PuO_2 + UO_2$) and structural stainless steel material) can penetrate through the grid plate and relocate downwards under gravitational force. The ensuing interaction between molten core materials and liquid sodium coolant (called as Molten Fuel Coolant Interaction (MFCI)) in the lower plenum causes the fragmentation of molten core materials on the order of few microns to millimeters (Gluekler et al., 1977; Sowa et al., 1976). The fragmented particles settle on the core catcher plate provided below the core support structure and form the debris bed. The formation of particulate debris bed is most anticipated, as the molten fuel and stainless steel have the strong tendency to get fragmented upon contact with liquid sodium. Hence the long term coolability of the particulate debris bed configuration (i.e. Post Accident Heat Removal – PAHR) and its recriticality potential are the major issues to be considered in the further evaluation of accident sequences (Kazimi and Chen, 1978; Waltar and Reynolds, 1981; Bhaskar Rao et al., 1994). In general, the long term coolability and recriticality potential of the debris bed are strongly influenced by the particle size distribution of fuel and stainless steel fragments and their way of settlement over the core catcher plate (Gabor et al., 1974; Dhir and Catton, 1976). The melt fragmentation process during MFCI decides the overall particle size distribution in the debris bed and the subsequent settling behaviour of fuel and stainless steel particles in the sodium pool determines their composition and size distribution along the bed height (i.e., bed thickness). The particle settling process following the fragmentation influences the debris bed characteristics in many ways. The difference in settling velocity of various size particles of different core materials tends to produce particle size and material stratification within the debris bed. This could affect the recriticality potential of the debris bed, effective bed thermal conductivity and also leads to variation in volumetric power level within the debris bed and depth dependent permeability for the coolant. Moreover, settling takes time during which the particles are quenched and solidified due to advantageous heat transfer conditions of the surrounding highly conductive sodium pool. Also, the bed depth increases gradually from a shallow, easily cooled configuration into a deep bed configuration. The settling and quenching behaviour of stainless steel and fuel particles in sodium are different, due to variation in their physical properties and size distribution (Chawla et al., 1981; Schins and Gunnerson, 1986). Hence, a differential settling process along with different heat removal rates from the particles is expected following the core relocation scenario, and this has been investigated in the present study to evaluate the composition profile and initial temperature of the particulate debris bed formed over the core catcher plate in pool type SFR.