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Experimental analysis of heaping and self-levelling phenomena in core debris using lead spheres

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ABSTRACT

The phenomena of core debris heaping and self-levelling on the core catcher plate are important from cooling considerations and also from recriticality aspects to ensure the safety of the reactor main vessel after the accident. A series of experiments is conducted in water, with funnel guided pouring of lead spheres on to a flat collector plate to mimic the heaping behaviour of core debris in sodium on core catcher plate. The rationale behind the choice of Lead–water pair is that their density ratio is equal to that between the nuclear fuel and the coolant in the reactor. From dimensional analysis it is shown that that repose angle of the heap (θ) is a function of particle Reynold's number (Re), Froude number (Fr) and Archimedes number (Ar) apart from density ratio and linear dimension ratios. Using the experimental data obtained from systematic parametric studies, the functional dependence of repose angle on Re, Fr and Ar is determined and the following empirical correlation is developed.

$$\theta = 26Re^{-0.38}Fr^{0.15}Ar^{0.20}$$

In the nuclear reactor, the decay heat generated within the core debris leads to natural convection and then local boiling within the coolant because of which self-levelling of the heap is expected to occur. To understand the evolution of repose angle with time, experiments have been conducted with bottom heated lead spheres, in the second part of the study. About 25% reduction of repose angle is observed in the first half an hour of heating in the natural convective regime itself which serves to reduce the possibility of coolant dryout occurring within the debris bed. But perfect levelling leading to a plane level is not achieved in the experiments with lead spheres.

1. Introduction

A severe accident such as core disruptive accident in a Fast Breeder Reactor (FBR) is a rare occurrence, the probability of occurrence being $<10^{-6}$/reactor year. Even though it is a beyond design basis accident, engineered safeguards such as the core catcher plate are provided to mitigate the consequences of such an accident. Molten Fuel Coolant Interactions (MFCI) can happen in a FBR when there is a severe accident in the reactor in which the fuel contained in the core can melt and come in direct contact with the coolant. The molten core, after breaching the grid plate, undergoes fragmentation in sodium contained in the lower plenum and eventually settles upon the core catcher placed at the bottom of the main vessel. Though nuclear fission reaction has long before ceased due to fuel dispersal leading to subcriticality, the core debris continues to generate heat from the decaying fission products. Therefore core debris settled on the core catcher plate is a source of heat which is removed by natural circulation of the coolant through the decay heat removal systems. The accident scenario is pictorially represented in Fig. 1.

In the safety analysis of FBRs, Molten Fuel Coolant Interactions are analysed for their potential to cause hazard from the coolability aspect and from the reconfiguration aspect, after the debris settles on the core catcher. This means that dry out of sodium should not happen within the debris bed and the configuration of the debris bed should not lead to recriticality to start a fission reaction again. The size of the debris and the repose angle on the core catcher chiefly govern these two aspects.

Self-levelling of the debris on the core catcher plate will help to increase the surface area which will help to enhance the heat transfer rate from the debris. The maximum height of the heap comes down with levelling and hence reduces the chance of dryout happening within the volumetrically self-heated bed. Dryout can lead to remelting within the debris leading to compaction which

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Nomenclature

d	diameter of particle
g	acceleration due to gravity
h	height of fall
k	neutron multiplication factor
m	mass of debris
t	time
v	velocity of particle
H	height of heap
R	radius of heap

Greek symbols

$\Delta\rho$	density difference between particle and the fluid
μ	viscosity of the fluid
ρ	density of the particle
ρ_f	density of the fluid

Subscripts

eff	effective
f	fluid
m	model
p	prototype
s	solid particle

Pi numbers

θ	Repose angle
Ar	Archimedes number
Fr	Froude number
Re	Reynolds number

can further reduce the coolability of the debris. Deep debris beds are likely to dryout faster because there is a strong probability of coolant starvation because of the bubbles getting trapped deep within leading to local hotspots. Self-levelling also helps to reduce the effective neutron multiplication factor by allowing more neutron leakage, thus decreasing the chances of recriticality. In the upcoming Japanese reactor JSFR, a multi tray core catcher is planned and the self- levelling mechanism is relied upon for even distribution of the debris [1]. They perceive self-levelling mechanism as the mechanism by which the debris depth will be automatically regulated to the level below which sodium boiling will not happen.

In the present work, heap formation is studied by allowing Lead spheres to fall on a circular plate. Lead is used as a simulant material since its density is close to that of nuclear fuel comprising of uranium di oxide and the viscosity of water at elevated temperature is close to that of liquid sodium. A series of experiments is conducted and an empirical correlation is developed between the relevant dimensionless groups from experimental results. The correlation is validated with the experimental data available in literature from the work carried out at CEA, Grenoble [2]. The self-levelling of the heat generating debris heap due to the coolant boiling within the debris is also addressed in the second part of the study by heating the debris through the bottom of the collector plate and assessing the evolution of repose angle with respect to time.

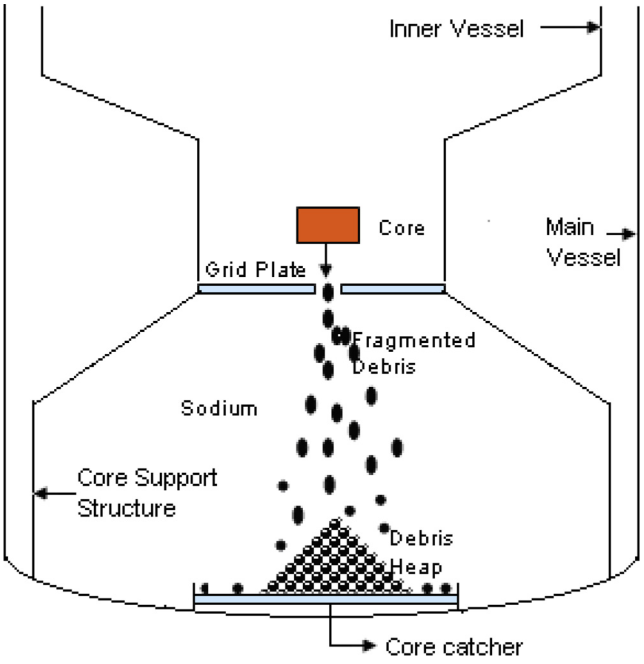

Fig. 1. Core debris on core catcher plate.

1.1. Need for the study

As stated earlier, a flat debris bed with its larger surface area to volume ratio poses less threat from the recriticality point of view and also from cooling considerations. Thermal–hydraulic analysis of the reactor lower plenum, with the core catcher containing the core debris, requires the size and shape of debris on the core catcher as input in order to estimate the temperature distribution on the core catcher plate. The geometrical shape of the debris bed influences the neutron multiplication factor k_{eff} [3]. A flat bed can reduce k_{eff} by promoting neutron leakage and thus exclude the chances of recriticality within the core debris. The debris heap profile and its evolution with time is an important input for reactor physics calculations to determine k_{eff} accurately. Hence the present study aims at assessing the heaping pattern and self-levelling behaviour of core debris on the core catcher from laboratory scale experiments. An empirical correlation for the static repose angle will be developed from the experimental data.

A few noteworthy research efforts in this particular research area are summarised in this section. In Europe, research program has been carried out by CEA where copper spheres in water have been used to study the heaping phenomenon and the results extrapolated to the UO_2-Na system [2]. The maximum angle of repose measured in air was 30° and that with water was 23°. In the core catcher design of Superphenix-1, heaping of debris was considered assuming that particles come from one spot on the lower plate of grid plate and the angle of repose was 24° [4]. Cheng et al. [5,6] have studied the self-levelling aspects of a debris heap by nitrogen gas injection through the debris bed. They have also studied the effect of particle size, shape and density, geometry effect, water depth, boiling mode such as depressurization or bottom heating and bubbling rate on the self-levelling behaviour.

Zhang et al. [7,8] have obtained a palette of data for studying the influence of levelling on gas flow rate, water depth, particle size and particle density by depressurization boiling method of the coolant through the debris bed. In these papers cited from the