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Void fraction and heat transport in two-dimensional mixed size particle beds with internal heat sources

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Abstract

The paper discusses the boiling heat transfer from a porous bed with internal heat sources and refers to the configuration in a nuclear reactor after a partial core melt. The flow of coolant, the temperature and the local liquid/vapor distribution were investigated in a two-dimensional configuration. Experiments were conducted using monodisperse beds as well as a mixture of two different particle sizes with a total porosity below 20%. In some tests the bed was supported by a shell of porous material to create a gap along the bottom of the test container. Water was used for tests up to 9% of the critical pressure, while other tests were made with R134a up to 44% of the critical pressure. The maximum heating rate realized inductively was 730 kW/m^2. The experiments have been compared to analytical results with a one-dimensional approach.

It is shown that in contrary to the situation in small cylindrical configurations the heat transfer was increased by large buoyancy driven convective flows. If there was a gap along the container bottom an additional flow of liquid improved the coolability of the bottom region even if the upper part of the particle bed was already overheated. In case of high density ratios (water at low pressure), the measurements indicated a strong enhancement of the coolant flow above a certain minimum heating rate resulting in decreasing vapor fraction values which were nearly independent of the system pressure. This was assumed to be caused by the appearance of vertical channels through which the vapor could flow through the particle bed.

1. Introduction

For the assessment of the passive safety features of nuclear reactors, it is of fundamental interest to understand the boiling phenomena in heat producing porous media, especially for an analysis of the process of a hypothetical severe accident with a partial core melt. The liquid melt can relocate to the lower plenum of the pressure vessel and solidify in form of particles in the water remaining in the lower plenum. It is possible that the melt gets totally fragmented and a loose-packed porous debris bed develops.

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Nomenclature

d	particle diameter (m)
f	volumetric fraction
g	gravitational constant (m/s^2)
h	height of particle bed (m)
J	Leverett function
K	permeability (m^2)
l	gap length (m)
n	number
p	pressure (Pa)
s	gap width (m)
u	fluid velocity (m/s)
v	volume flow/area within bed (m^3/s m^2)
z	vertical coordinate (m)

Greek letters

α	local void (vapor) fraction
ε	porosity
η	passability
κ	relative permeability
ρ	density (kg/m^3)
σ	surface tension (N/m)
Θ	angle of wetting

Several experimental researches are reported in literature, in which the complete process of the melt relocation in an half-spherical, partly water filled container over the cooling and solidification to the final configuration was investigated. Using ceramic materials like aluminum oxide or realistic uranium/zirconium oxide mixtures, the melt temperatures were rather high. Therefore, merely the surface temperatures of the container could be monitored and little insight to the cooling phenomena inside the melt was given. Denhem et al. (1992) investigated the case of molten uranium oxide falling into a deep pool of water. They reported a fragmentation of the melt to particles with a diameter in the range from under 0.1 mm up to 10 mm. The mass mean diameter was about 3–4 mm. Similar results have been presented by Magallon et al. (1998). In their experiment a prototypic melt (UO_2, ZrO_2 and Zr) fragmented to particles with an average diameter near 4 mm. A very fast cooling down of the particle bed was measured by thermocouples on the surface of the container. No measurements could be made inside the particle bed. Maruyama et al. (1999) used aluminum oxide and described a massive block with a significant porous layer along the surface and a resulting gap of 1–2 mm between this block and the container wall.

In other experiments, the basic phenomena inside a porous media with internal heat sources were investigated. In the usual configuration, a bed of steel spheres having uniform size is located in a cylinder made of an insulating material (glass, ceramics) and heated by an induction coil surrounding the cylinder. The bottom is adiabatically sealed and the configuration is cooled by a liquid layer above the bed. There is a vast number of papers concerning this problem (e.g. Corey, 1977; Hardee and Nilson, 1977; Bau and Torrence, 1982; Catton and Jakobsson, 1987; Dhir, 1994). In such a nearly one-dimensional setup, flooding usually occurs at a discrete heating power. Above this critical power the steady state cooling process becomes unsteady and the bed will become completely dry and uncoolable as the rising vapor prevents the liquid from penetrating the particle bed from above. This limitation of the heat input scaled by the horizontal cross-sectional area is called the “dryout heat flux” which depends on the average particle diameter, porosity and thermodynamic properties of the fluid (e.g. heat of evaporation and density ratio of liquid and vapor). Lipinski (1981) and Dhir (1994) give a semi-empirical model based on relative permeabilities to calculate the vapor fraction distribution in such a configuration (see Section 4). Using this information the dryout heat flux can be evaluated.

In another experiment, a mixture of particles of different size and shape was used. Miyazaki et al. (1987) mixed small metal cylinders with ceramic spheres. As no relocation occurred, the results were similar with predictions from the model for which they used an average particle diameter. Several authors suggest to use the so called “Sauter”-diameter, which is based on the mean hydraulic diameter of a flow path through the particle bed (Dhir, 1994; Kaviany, 1995) given by the equation

$$d_{\text{avg}} = \frac{1}{\sum f_i/d_i} = \frac{\sum n_i d_i^3}{\sum n_i d_i^2} \tag{1}$$

in which f_i is the volume fraction of a certain particle size and n_i is the number of particles having this size. Miyazaki et al. (1987) took the number of the particles (equivalent to the number of the pores between these