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Pressure drop and average void fraction measurements for two-phase flow through highly permeable porous media

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ABSTRACT

The modeling of pressure drop for two-phase flows through porous media is a key point to assess the coolability of debris beds resulting from nuclear severe accidents. Models involve several parameters which are non-linear functions of the void fraction, e.g. relative permeabilities. Their identification requires that experimental data include the measurement of void fraction. This paper presents a new technique developed to reach this objective. The method is based on the use of a capacitance probe and has been validated by comparison with a weighing method. The validation has shown that the accuracy is better than 10%. The measurement device has been implemented in the CALIDE facility, at IRSN, which has been designed to perform air–water flow through debris bed. Tests have been carried out with beds made of single size 4 mm and 8 mm beads. Measurements of pressure drop and average void fraction are reported in the paper, for air and water flow rates representative of flows that would result of either the reflooding of the damaged core or the cooling of corium debris in a stagnant pool of water. Finally, the pressure drop models used in severe accident simulation codes, based on generalizations of the single-phase Ergun law, have been assessed against the new data. It has been observed that generalized Ergun laws including an interfacial drag term accurately predict the pressure drop and the void fraction for flows with a zero net water velocity.

1. Introduction

The understanding of two-phase flow through high permeability porous media is of interest in several applications such as chemical reactors, oil/gas production or soil physics. In the field of nuclear safety analysis, the study of such flows has become of great importance after the TMI-2 accident (1979), where the injection of water on hot debris bed have stopped the progression of melting and led to keep the corium inside the reactor vessel (Broughton et al., 1989). By now, the assessment of debris coolability remains an open question. To address it, there is a need for a reliable thermal–hydraulic model able to estimate the debris heat removal rate during quenching or dry-out.

Several experimental investigations have been carried out to help modeling. Dry-out experiments (Hardee and Nilson, 1977; Dhir and Catton, 1977; Lipinski, 1984; Decossin, 1999) and reflood tests (top flooding: (Cho et al., 1984; Ginsberg et al., 1982; Tutu et al., 1984a; Tung and Dhir, 1988); bottom flooding: (Hall and Hall, 1981; Tutu et al., 1984c; Tung and Dhir, 1986)) have been performed, providing global parameters: outlet steam flow rate, quench front velocity, etc. The instrumentation was scarce so that only 0D/1D models have been developed, based on the counter current flow limitation (CCFL) and on correlations for the friction laws (Lipinski, 1982; Reed, 1982; Hu and Theofanous, 1991; Tung and Dhir, 1988; Schulenberg and Müller, 1987). 2D/3D models, which provide detailed flow fields (Fichot et al., 2006; Burger et al., 2006), have been developed. However, due to the lack of accurate local measurements in debris beds, models could not be validated. It is worth noticing that new data are available on large scale reflood tests (Chikhi et al., 2015). Two kinds of closure laws are required in these models: friction laws and heat transfer laws.

Since the generalization of Darcy's law by Muskat (1937), pressure drop models for two-phase flow through porous media involves parameters non-linearly dependent on saturation. In the

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context of nuclear safety, it is generally assumed (Schmidt, 2004) that the pressure drop is a function of the superficial gas and liquid velocities and of the void fraction (or gas saturation), i.e., $\Delta P = f(V_l, V_g, \alpha)$. Therefore, the inclusion of void fraction measurements in experimental data would seem an obvious requirement. And yet, the only data available in this field come from the experiments of Tutu et al. (1984b) with a zero net water flow. Schmidt (2004) compared the friction laws with these experimental data and showed that the pressure drop models should include an explicit interfacial friction term. Tung and Dhir proposed a modification of their model to take into account this feature by introducing a flow regime map (Tung and Dhir, 1988). Nevertheless, due to the lack of experimental data, the flow regime map could not be validated.

The bibliography related to the transposition of air–water flow to steam–water flow through porous media is quite scarce in the nuclear field. By now, there is no definitive conclusion on in this subject. Some studies have been done in petroleum and geothermal engineering field and a large review of results on steam–water relative permeability (laminar regime) can be found in Counsil (1979): Corey's equations to characterize steam–water relative permeability (Corey, 1977), Chen's drainage relative permeability curves (Chen et al., 1978) and Horne's curves relative permeability curves (Horne and Ramey, 1978). Few attentions have been paid to steam–water relative passability (inertial regime). More recently, discrepancies between steam and nitrogen injection have been reported in Jabbour et al. (1996).

The aim of the present paper is to propose an original method to measure the void fraction for air–water flows through nuclear-like debris bed. The method is based on the use of capacitance probes, widely used in soil physics (Zakri et al., 1998). It is presented in detail in Section 3. The measurement set-up has been implemented in the CALIDE facility (Chikhi et al., 2013), which is an air–water loop designed to generate two-phase flows through porous media. The CALIDE facility and the test conditions (flow regime and debris bed characteristics) are presented in Section 2. The capacitance probe method has been validated by comparison with a weighing method (Section 3). Different kinds of particles have been used to make the porous beds: glass beads, ceramic prisms and ceramic cylinders. Finally, pressure drop measurements have been performed on beds made of single-size spherical particles. Two beds have been built with 4 mm and 8 mm diameter spheres. The pressure drop have been measured for several gas and liquid mass flow rates that are representative of severe accident conditions. Section 4 is devoted to the presentation of these original experimental data. In Section 5, the classical pressure drop models cited above (Lipinski, Reed, Hu and Theofeanous, Tung and Dhir, Schulenberger and Muller), which are implemented in severe accident codes, are assessed against the experimental results.

2. Experimental set-up

2.1. The CALIDE loop

The CALIDE facility is an air/water single- and two-phase flow loop designed for pressure drop vs flow rate measurements for flow through porous media (Clavier et al. (2015) and Fig. 1). The test section containing the bed is made of a Plexiglas pipe (500 mm high and 94 mm diameter) which allows flow visualization. Air is supplied from the bottom and flows up through the bed, while water can flood the bed either from the top or the bottom, providing either co-current or counter-current flows. A stainless steel wire mesh is placed at the bottom of the test section to support the bed. This wire mesh has a negligible impact on the total pressure drop measured across the test section.

The fluid flow rates are measured and controlled by five high precision Bronkhorst® flowmeters with specific measuring ranges (see Table 1). Six radial holes uniformly distributed along the test section allow pressure tapping at different levels inside, downstream and upstream the debris bed. Pressure drops are measured by two Rosemount-3051® differential pressure sensors (see Table 2). A thermocouple records the temperature at the top of the test section. This measured temperature is used for fluid viscosity μ and density ρ calculation using tabulated values (Lide, 1990). The density is calculated for the average pressure to account for the gas compressibility (see Clavier et al. (2015) for more details).

2.2. Debris bed

A comprehensive review of the geometrical characteristics of nuclear debris beds can be found in Chikhi et al. (2014). One of the main conclusions of this study was that the particle size ranges from 0.3 to 10 mm. The porosity ranges from 0.35 to 0.55. It was also shown that, as far as pressure drop estimation is concerned, a debris bed made of polydisperse and non-spherical particles can be represented by an equivalent bed made of single-sized spherical particles either in the study of quenching or dry-out situation.

To validate the void fraction measurement method, a bed made of particles with identical shapes has been used. Several shapes were tested: spheres (glass), prisms (ceramic) and cylinders (ceramic) (Fig. 2). Their geometrical characteristics are given in Table 3.

For the integral tests devoted to pressure drop measurements, two beds have been studied, made of 4 mm and 8 mm glass beads. The bed properties have been measured and are given in Table 4.

Bed porosities have been measured as the pressure losses are very sensitive to this parameter. To determine the bed porosity, the test section was filled with water with a mass m_w. The porosity is deduced using the water density ρ_w:

$$\varepsilon = \frac{4m_w}{\rho_w \pi D^2 H}, \tag{1}$$

where H is the test section height and D the test section diameter.

According to the particle diameter and to the porosity, two other bed characteristics can be calculated, the permeability K and the passability η:

$$K = \frac{\varepsilon^3 d^2}{h_K (1-\varepsilon)^2}, \tag{2}$$

$$\eta = \frac{\varepsilon^3 d}{h_\eta (1-\varepsilon)}, \tag{3}$$

where $h_K = 181$ and $h_\eta = 1.63$ are two empirical constants, which have been determined by fitting Ergun's law (Ergun, 1952)

$$-\frac{\partial P}{\partial z} + \rho g = \frac{\mu}{K} U + \frac{\rho}{\eta} U^2, \tag{4}$$

against experiments as presented in a previous paper (Clavier et al., 2015) in the case of one-phase flows through beds packed with single-sized beads.

2.3. Flow regime and test conduct

The water and air flow rates have been chosen to be representative of water and steam filtration velocities during the reflood of a damaged core. Considering a reflood at low pressure in a French 1300 MWe PWR, the reflood mass flow rate is equivalent to a filtration velocity ranging from 5 mm/s to 32 mm/s. The steam