Annals of Nuclear Energy 112 (2018) 769–778

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Adequacy of effective diameter in predicting pressure gradients of air flow through packed beds with particle size distribution

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ARTICLE INFO

Article history:
Received 21 April 2017
Received in revised form 28 June 2017
Accepted 20 August 2017
Available online 14 November 2017

Keywords:
Pressure gradient
Single-phase flow
Effective diameter
Particle size distribution
Particle shape

ABSTRACT

In the late phases of severe accidents in nuclear power plants, in order to ensure the long-term coolability of the debris bed on a reactor containment floor, it is crucial to cool down and stabilize molten core debris, which has an internal heat generation by decay heat. Therefore, it is of key importance to continuously supply water into a debris bed, which is affected by the pressure drop depending on the characteristics of debris bed such as bed porosity, particle morphology, particle size distribution, etc. Thus, in the present work, the influence of particle size distribution and the adequacy of mean diameters for predicting pressure gradients in particle beds were evaluated. Experimental data were obtained on the pressure gradients of air flow in packed beds composed of either spherical or cylindrical stainless steel particles having a size distribution of 1–10 mm. The results were compared with the values calculated by a proposed model in our previous work. When the area mean diameter was adopted as the effective particle diameter, the measured pressure gradients of air flow through each spherical particle bed with a particular size distribution agreed with the calculated values within a mean absolute percentage deviation of 9%. For a cylindrical particle bed with a particular size distribution, the measured pressure gradients agreed with the calculated values within a mean absolute percentage deviation of 12% when adopting the area mean diameter calculated using the equivalent diameter, the product of the Sauter diameter and particle shape factor as the effective diameter for non-spherical particles. This selection of mean and effective diameters produced the best fit among several candidates. Thus, we propose the area mean diameter (calculated using the equivalent diameter) as the effective diameter for determining the hydraulic diameter affecting fluid resistance in porous beds composed of non-spherical particles with a particular size distribution.

1. Introduction

When a core damage accident occurs in light water nuclear power plants, the molten core material (corium) can fall and relocate into the lower plenum of the reactor pressure vessel. The corium can then further progress to the ex-vessel phase unless sufficient cooling is provided. During the progression of a corium release resulting from the failure of a reactor pressure vessel, corium interacts with water supplied either by the cavity flooding system, containment spray, or other systems as the severe accident management strategy in the reactor cavity. Fuel coolant interaction (FCI) results in the fragmentation of melt jets. The fragmented melt settles down with quenching and is finally heaped on the reactor containment floor.

In the late phases of severe accidents in nuclear power plants, in order to ultimately terminate severe accident progression, it is crucial to cool down and stabilize molten core debris, which has an internal heat generation by decay heat. This causes that the core debris conditions on the containment floor define the preconditions of the molten core concrete interaction, which results in concrete floor erosion. This threatens the integrity of the containment building, the final physical barrier (in terms of defense-in-depth) that prevents the release of radioactive material into the environment.

Therefore, it is of key importance to ensure the long-term coolability of a debris bed that has been relocated onto the reactor containment floor. This can be accomplished by continuously supplying water to the internal heat generating corium debris bed. The effectiveness of supplying water into a debris bed is determined by the pressure drop through the debris bed. Thus, it is necessary to investigate the pressure drop mechanisms in a debris

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https://doi.org/10.1016/j.anucene.2017.08.053
0306-4549/

Nomenclature

A_p	surface area of the particle (m^2)
C_1, C_2	Ergun constants (–)
d_a	area mean diameter (m)
d_{eq}	equivalent diameter (m)
d_l	length mean diameter (m)
d_m	mass mean diameter (m)
d_n	number mean diameter (m)
d_p	spherical particle diameter (m)
d_{sd}	Sauter diameter (m)
d_t	inner diameter of test section (m)
f_j	the ratio of the number of particles of the corresponding size in the bed (–)
g	acceleration of gravity (m/s^2)
Ga_i	modified Galileo number (–), $Ga_i = (\rho_i/\mu_i)^2 g(d_p\varepsilon/(1-\varepsilon))^3$
k_0	shape parameter of the cross-section of the channel (–)
K	permeability (m^2)
m_p	mass of particle (kg)
p	pressure (Pa)
Re_p	particle Reynolds number (–), $Re_p = \rho_i V_{si} d_p/\mu_i(1-\varepsilon)$
V_p	volume of the particle (m^3)
V_{si}	superficial velocity (m/s)
V_t	volume of the test section (m^3)
d_j	particle size (m)

Greek symbol

β	the ratio of pore diameter to throat diameter (–)
ε	porosity (–)
η	passability (m)
μ	dynamic viscosity (Pa·s)
τ	tortuosity (–)
ρ	density (kg/m^3)
φ	shape factor of particle (–)
ψ_i	dimensionless pressure drop (–), $\psi_i = (-dp/dz\text{-}\rho_i g)/\rho_i g$

Subscript

i	fluid phase; l = liquid, g = gas
p	particle

bed, which are characterized by geometric parameters such as bed porosity, particle morphology, particle size distribution, etc. The characteristics of a debris bed on a reactor containment floor under hypothetical accident conditions can be found from the results of previous investigations on FCI experiments (Moriyama et al., 2005; Magallon, 2006). The debris bed is comprised of irregularly shaped particles with a particle size distribution ranging from a few of micrometers to approximately 10 mm, and it has axial and radial stratification (Magallon, 2006; Karbojian et al., 2009).

Therefore, to consider the effects of hypothetical debris bed characteristics on the pressure gradients of flow, many researchers have suggested empirical or semi-empirical models substantially based on the Ergun equation (Ergun, 1952), which is expressed as follows:

$$-\frac{dp}{dz} - \rho_i g = \frac{C_1\,\mu_i\,(1-\varepsilon)^2}{\varepsilon^3\,d_p^2}V_{si} + \frac{C_2\,\rho_i\,(1-\varepsilon)}{\varepsilon^3\,d_p}V_{si}^2. \quad (1)$$

The first term of the right-hand side is the viscous energy loss term, while the second term is the inertial loss term, where C_1 and C_2 are the empirical Ergun constants, having values of 150 and 1.75, respectively. The dynamic viscosity and the density of the i-phase fluid (i = l and g for liquid and gas) are μ_i and ρ_i, respectively. The pressure loss through porous media is expressed as $-dp/dz$ when V_{si}, d_p, and ε are the superficial velocity of fluid, the particle diameter and the bed porosity, respectively. The bed porosity is calculated as follows:

$$\varepsilon = 1 - \frac{\sum(m_p/\rho_p)}{V_t}, \quad (2)$$

where $\sum m_p$ is the total mass of particles in the test section, ρ_p is the density of particles, and V_t is the volume of the test section.

The Ergun equation above-described is a momentum conservation equation for predicting pressure drop of single-phase flow in homogeneous beds consisting of mono-size spherical particles. Thus, in order to apply the Ergun equation to heterogeneous beds composed of non-spherical particles with a particular size distribution such as the debris bed on the reactor containment floor, the evaluation on both the adequacy of Ergun constants and the effective diameter for determining the hydraulic diameter affecting fluid resistance in heterogeneous beds is crucially important.

Accordingly, to consider the influence of particle morphology on pressure gradients of single-phase flow, many prior researchers have suggested modifying the Ergun constants (C_1 and C_2) by substituting the Sauter diameter for the effective particle diameter, as listed in Table 1 (Leva, 1959; Handley and Heggs, 1968; Macdonald et al., 1979; Ozahi et al., 2008). The Sauter diameter of a particle is defined as the diameter of a sphere that has the same volume/surface area ratio as the particle of interest. It is expressed as follows:

$$d_{sd} = \frac{6V_p}{A_p}, \quad (3)$$

where V_p is the volume of the particle and A_p is the surface area of the particle.

Foumeny et al. (1993, 1996) suggested $C_1 = 130$ and $C_2 = (d_t/d_p)/(0.335d_t/d_p + 2.28)$ for spherical particles, and $C_1 = 211$ and $C_2 = 3.81 - 5.265/(d_t/d_{sd}) - 7.047/(d_t/d_{sd})^2$ for cylindrical particles, using the ratio of tube diameter d_t and the Sauter diameter d_{sd}. Nemec and Levec (2005) suggested including the shape factor φ in the Ergun constants, such as $C_1 = 150/\varphi^{3/2}$ and $C_2 = 1.75/\varphi^{4/3}$ for cylindrical particles, and $C_1 = 150/\varphi^{6/5}$ and $C_2 = 1.75/\varphi^2$ for polylobed particles. The shape factor is the ratio of the surface area of a sphere with the same volume as the given particle to the actual surface area of the particle, and is defined as follows (Wadell, 1935).

$$\varphi = \frac{\pi^{\frac{1}{3}}(6V_p)^{\frac{2}{3}}}{A_p} \quad (4)$$

Table 1
Modification of Ergun constants with the Sauter diameter.

Model	C_1	C_2
Leva (1959)	200	1.75
Handley and Heggs (1968)	368	1.24
Macdonald et al. (1979)	180	1.8 (smooth particles) / 4.0 (rough particles)
Ozahi et al. (2008)	160	1.61