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Original Research Paper

Determination of pressure drop for air flow through sintered metal porous media using a modified Ergun equation

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ABSTRACT

Sintered metal porous media currently play a significant role in a broad range of industrial equipments. The flow properties in porous media are generally approximated by Forchheimer regime or Ergun regime. In this study, a modified Ergun equation is developed to correlate the pressure drop with flow rate. Experimental and theoretical investigations on pressure drop are conducted with a series of metal-sintered porous media. A viscous drag region and a form drag region are defined with Reynolds number $Re = 1$ and $Re = 10$ as the boundary. The coefficient α and β in the equation are determined by, α first in the viscous drag region, then β in the form drag region. It is confirmed that theoretical pressure drop versus flow rate in terms of the modified Ergun equation provides close approximations to the experimental data. In addition, it is found that compressibility effect can aggravate the pressure drop. It is also concluded that there exists a range of transitional diameters, within which the wall effect on the pressure drop would become extraordinarily uncertain.

1. Introduction

Air flow through porous media is universal in a broad range of industrial equipments, e.g., filters, heat exchanges, catalytic reactors and pneumatic silencers. Porous media comprise extremely complicated flow paths, and thus cause pressure drops when they are connected in a pneumatic circuit. Therefore, an accurate prediction of the pressure drop is crucially needed for performance evaluation. A number of studies [1–4] have demonstrated the physics of flow through porous media under the assumption that the internal structure is isotropic and homogeneous. Their findings show that the Darcy regime can predict flow behavior properly when the flow is dominated by viscous effect. Meanwhile, when inertial effect becomes dominant, the pressure gradient versus flow velocity exhibits a nonlinear relation.

Some researchers use idealized geometrical shapes to develop theoretical models for the structure of porous media. Almeida [5] and Andrade [6] investigated fluid flow through ramified structures by directly simulating 2D Navier–stokes equations. Rojas and Koplik [7] theoretically studied incompressible flow at a nonzero Reynolds number in a 2D model of porous media. Bogdanov [8] provided a 3D numerical model for single-phase, slightly compressible flow through fractured porous media. Morais [9] studied fluid flow through 3D disordered porous media by direct numerical simulation. Mauroy [10] represented porous media with a branched tree model to help understand flow properties. Machado [11] simulated the two-dimensional flow in porous media by means of the lattice Boltzmann method.

Some researchers attempt to correlate experimental data to assess the flow properties of porous media. Probably the two most known theoretical relations should be the Forchheimer equation [12] and the Ergun equation [13,14]. Early experimental works by Beavers et al. [15,16] indicate that the flow characteristics of fibrous porous media can be clarified by Forchheimer equation with appropriate permeability and inertial coefficient. Montillet et al. [17] proposed a correlating equation to predict pressure drops through packed beds and provided experimental evidence for validation. Antohe et al. [18] presented a study that uses the Forchheimer extended flow model to compute the permeability and inertial coefficient for the compressed aluminum matrices. Dukhan and Minjeur [19] suggested the use of two permeabilities,

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one for the Darcy regime and the other for the Forchheimer regime, to depict pressure drop properties. In addition to the Forchheimer equation, the Ergun equation has also received great attention. Dukhan [20] verified the validity of the Ergun-type relationship to characterize pressure drop with respect to flow velocity and confirmed that both permeability and inertial coefficient correlate well with porosity. Du Plessis [21] theoretically derived a momentum transport equation for fully-developed flow in porous media which is based on Ergun equation. Liu [22] described the friction characteristic based on the measured pressure drop of air through foam matrixes using an empirical equation which is similar to Ergun equation. In above studies, porous media with a high range of porosities (over 80%) are commonly adopted. When airflow pass through the media, compressibility is negligible and velocity is generally considered constant [23–25].

The traditional Forchheimer equation or Ergun equation mainly includes the effects from viscosity and inertia. However, some other factors might also affect the pressure drop characteristics. Mehta and Hawley [26] used a modified Ergun equation to account for the friction from the wall effect. Their results show that the wall effect exists when the column to particle diameter ratio was less than 50. Eisfeld and Schnitzlein [27] investigated the influence of the container walls on the pressure drop of packed beds and found that the influence is caused by the counteracting effects of the wall friction and the increased porosity near the wall. Felice and Gibilaro [28] presented a simple model for the effect of the container wall on the pressure loss in a fluid flowing through a bed of spheres. Dukhan and Mohamed [29] experimentally investigated wall and size effects on permeability and form drag coefficient. Cheng [30] proposed a capillary-type model based on a modified Ergun equation to investigate wall effect on the pressure drop in packed beds. Other than wall effect, compressibility effect also affects the pressure drop. Existing literature commonly neglect the velocity gradient in the flow direction, and this treatment works only for the loose porous media which cause slight pressure drop. In contemporary air bearing feeding systems, sintered metal porous media are gradually replacing the conventional orifices which easily cause pressure peak and clog problems. Belforte et al. [31,32] showed a considerable pressure drop between the upstream and downstream, and verified the capability of porous media to eliminate pressure peak compared with the case using an orifice. Furthermore, recently developed air conveyor systems [33,34] for large glass substrates also require the use of porous air supply pads to improve performance. In these applications, the effects, due to compressibility and confining wall, should also be discussed together with the effects from viscosity and inertia in order to provide an accurate correlation of pressure drop.

This study recasts the correlation for pressure drop in terms of a modified Ergun equation. Twenty-seven samples of sintered metal porous resistances were tested and results of the experimental study are presented. The effectiveness of the proposed correlation is also experimentally verified.

2. Theory

The pressure drop in porous media relates to the microstructure which is characterized by several factors, such as pore size, pore shape, and porosity. The physical model of airflow through porous media is schematically shown in Fig. 1, and the following assumptions are made to enable a theoretical derivation.

(1) The flow is steady and fully developed.
(2) The porous medium is isotropic and homogeneous, so its property parameters are constant.
(3) The flow is in the horizontal direction only.
(4) The flow through the porous medium remains isothermal.

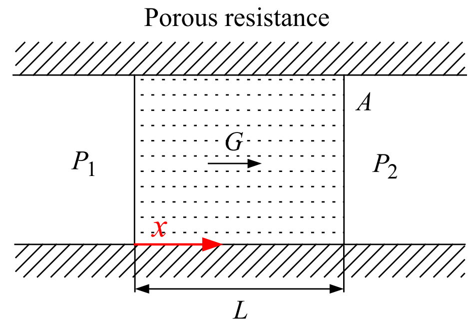

Fig. 1. Schematic of flow through porous medium.

Consequently, the mean flow velocity changes with the air density along the length direction and is written in the following form

$$v = \frac{G}{\rho A} \tag{1}$$

where v is the flow velocity, G is the mass flow rate, ρ is the density and A is the cross-sectional area.

Assuming that air is a perfect gas, density ρ is expressed as in the following form according to the ideal gas state equation

$$\rho = \frac{P}{RT} \tag{2}$$

where P is the pressure, R is the gas constant and T is the temperature.

Ergun [13] published an empirical relation for describing the pressure drop through porous media based on the porosity and a geometrical length scale as

$$-\frac{\mathrm{d}P}{\mathrm{d}x} = \alpha\frac{(1-\varepsilon)^2\mu}{\varepsilon^3 D_p^2}v + \beta\frac{(1-\varepsilon)\rho}{\varepsilon^3 D_p}v^2 \tag{3}$$

where α is a factor for the viscous drag portion of the pressure drop, β is a factor for the form drag portion, μ is the air viscosity, x is the displacement along the length direction, ε is the porosity and D_p is the particle diameter.

For a spherical particle, the specific surface area is

$$A_{sf} = \frac{6(1-\varepsilon)}{D_p} \tag{4}$$

Substituting Eqs. (1) and (2) into Eq. (3), the Ergun equation takes the following form for an incompressible flow

$$\rho\frac{\Delta P}{L} = \frac{\alpha(1-\varepsilon)^2\mu}{\varepsilon^3 A D_p^2}G + \frac{\beta(1-\varepsilon)}{\varepsilon^3 D_p A^2}G^2 \tag{5}$$

For the compressible case, substituting Eqs. (1) and (2) into Eq. (3) and integrating the pressure with respect to length, with the boundary conditions $P = P_1$ ($x = 0$ [m]), $P = P_2$ ($x = L$ [m]), obtain the following modified Ergun equation

$$\frac{\beta(1-\varepsilon)RT}{\varepsilon^3 D_p A^2}G^2 + \frac{\alpha(1-\varepsilon)^2\mu RT}{\varepsilon^3 A D_p^2}G + \frac{P_2^2 - P_1^2}{2L} = 0 \tag{6}$$

The Reynolds number Re based on porosity ε and particle diameter D_p is given by

$$Re = \frac{\rho v D_p}{\mu(1-\varepsilon)} \tag{7}$$

A dimensionless friction factor f is defined as

$$f = -\frac{\mathrm{d}P}{\mathrm{d}x}\frac{D_p}{\rho v^2}\left(\frac{\varepsilon^3}{1-\varepsilon}\right) \tag{8}$$