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Key Words: porosity, fluid flow, porous media, semi-empirical equation, packed bed, Furnas equation, size spherical packing system.

Summary

Fluid flow in porous media has received much attention in recent years because of its important role in a large variety of engineering and technical applications, such as filtration units, wastewater treatment, packed beds, and certain types of chemical reactors. The porosity is the most important property of a porous medium and it affects most of the physical properties of the medium. Semi-empirical modified equation for the porosity had been proposed depending on the parameters affecting the porosity for water flow through porous media for sphere particles of mono size packing system. The parameters affecting the porosity in the packed bed of sphere packing were found to be the particle diameters and bed diameter. Several types and kinds of packing materials with different sizes have been used in the packed bed such as Pea Gravel, Marbles, Glass Marbles, Plastic Marbles, Black Marbles, Clear Marbles, Acrylic balls and Glass spheres. The diameters of the packing materials used in this model are from the range of (0.2-0.89) cm, the porosity is from the range of (0.3-0.76), the bed diameters is from the range of (7.62-15.24) cm, velocity is from the range of (0.002 - 0.3) m/s, the pressure drop is from the range of (24.9–59097) Pa and the height of packing is from the range of (7.62 - 56) cm. The calculation results of the porosity modified equations have been compared with Furnas equation of porosity and with experimental results taken from documented literature data; the comparisons show a very good agreement between the porosity modified equation and experimental results.

Keywords:

Introduction

There has been an increase in interest in the effect of porous media, because of their extensive practical applications in geophysics, thermal insulation in buildings, petroleum resources, packed-bed reactors and sensible heat-storage beds (Beithou et al. 1998). Porous materials are encountered everywhere in everyday life, in technology, and in nature. The most important structural characteristics of porous media include porosity, radial variations in void fraction, specific lateral surface area variations etc (Foust et al. 1980). The porosity is the most important property of a porous medium and it affects most of the physical properties of the medium. For a homogeneous porous medium, the porosity may be a constant. But in general, the porosity is a space dependent. The porosity is affected by many variables that may be classified into the categories of particle properties, container properties and packing method (Cumberland and Crawford 1987, German 1989). The porosity (ε) is defined as the ratio of the void volume to the total volume of the bed (the volume fraction occupied by the fluid phase) (Leva et al. 1951), i.e:

$$\varepsilon = \frac{Volume\ of\ voids\ in\ a\ bed}{total\ volume\ of\ the\ bed} \qquad (1)$$

Other names given to the porosity are void fraction, fractional voidage, or simply voidage. The liquid in a porous media usually fills this voided volume. For spherical packing, geometric analysis predicts that the porosity will be constant with consistent packing methods, regardless of the diameter of the spheres (Geankoplis 2003).

The porosity has a great effect on the properties of porous media, a 1% decrease in the porosity of the bed produced about an 8% increase in the pressure drop (Leva 1959), whilst Carman reported a higher value, 10% increase in the pressure drop for every 1% decrease in porosity (Carman 1938).

Depending on the type of the porous medium, the porosity may vary from near zero to almost unity. The normal range of average void fraction was suggested to be from 0.36 to 0.43 (Motil and Nahra 2005). An equation for the porosity as a function of particle diameter and bed diameter in packed column with sphere packing has been proposed (Furnas 1931):

$$e = 0.375 + 0.34\frac{d_p}{D_r} \qquad (2)$$

Where d_p is the particle diameter in m and D_r is the bed diameter in m.

An empirical equation for the porosity in terms of dimensionless group for spherical particles with special reference to the effect of liquid addition was formulated. The author shows that the properties of both particle and liquid affect the packing behaviors significantly. Under given packing conditions, dry based porosity increases to a maximum and then keeps constant with the increase of liquid content. Particle size and surface tension are the main factors in the quantification of this porosity- liquid content relation (Feng and Yu 1998). A method to correct the effects of the variable porosity on flow through porous media by considering two distinct uniform void fractions was suggested by many anthers (Stanek and Szekely 1972, Stanek and Szekely 1973). A mathematical model to calculate the porosity of particulate mixtures from the knowledge of particle sizes involved and their proportion in the mixture was proposed (Ouchiyama and Tanka 1984). The influence of distribution of the particle size upon the density of granular material was studied (Fuller and Thompson 1987). Local voidage for mixtures of spheres packing (mono, binary and ternary) was studied by many authors and they found local voidage variations in the axial, radial and angular direction (Yu and Standish 1991).

The aim of this work is to propose a conceptually based and accurate semi-empirical equation model for the porosity in porous media as a function of particle diameter and bed diameter.

The second aim of this work was to study the effect of bed porosity on the pressure drop. The effect of different parameters on the porosity, like particles size and size distribution on the bed has been also studied.

Materials and Methods:

Description of the packing materials

In this work twenty sizes of spherical particles of different types were used. The spherical particles diameters were 0.213, 0.25, 0.259, 0.3048, 0.42, 0.51, 0.61, 0.635, 0.636, 0.655, 0.79, 0.99, 1.01, 1.03, 1.095, 1.27, 1.9, 1.905 and 8.89 cm. The experimental data for different types and sizes of packing materials have been shown in table 1 below; this table also shows the bed diameter and the height of packing used. The fluid used in this work was water, the properties was taken at city temperature (25°C); at this temperature is density and viscosity of water was found to be 997.07 kg/m^3 and 0.89*10^{-3}kg/m.s respectively (Perry et al. 1997).

Description of the apparatus used for packed bed

A schematic diagram of the apparatus used is shown in Figure 1. The packed bed column was made of glass tube (Q.V.F). The Q.V.F glass contains two pressure taps. The pressure taps were chosen to be small in diameter (2 mm) and inserted flush to the inside wall of the tube to avoid fluid turbulence and determine the static pressure accurately. The first tap was placed down stream at a distance of 1 cm from the sieve, and the second was placed at a distance of 1cm from the top of the packing. The distance between the inlet of the column and the sieve (packing rest) was 25 cm to avoid fluid turbulence at the bed inlet.

Table 1 Experimental data for different types and sizes of packing

Types of packing materials	Particle diameters (cm)	Bed diameters (cm)	Height of packing (cm)
Glass spheres, black marbles, pea gravel	0.25, 0.635, 1.095, 1.27	8.89,15.24	38.1, 48.26, 45.72
Plastic marbles, pea gravel	1.27	8.89, 15.24	46.99
Pea gravel	0.655, 1.27, 8.89	8.89, 15.24	40.64, 60
Acrylic balls	0.635	8.826	28.25
Glass spheres	0.42, 0.51, 0.61, 0.79, 0.99	7.64	15.15
Glass spheres	0.42, 0.51, 0.61, 0.79, 0.99	7.62	20
Glass spheres	0.24, 0.42, 0.82, 0.6,1.03	7.64	15.15, 20
Black marbles	1.9	14.616	61.6, 67.3
Acrylic balls	0.655, 1.27	8	49.53
Clear marbles	0.636, 1.27	8	48.26, 50.8
Glass marbles	0.653, 1.27, 1.9	8	50.8

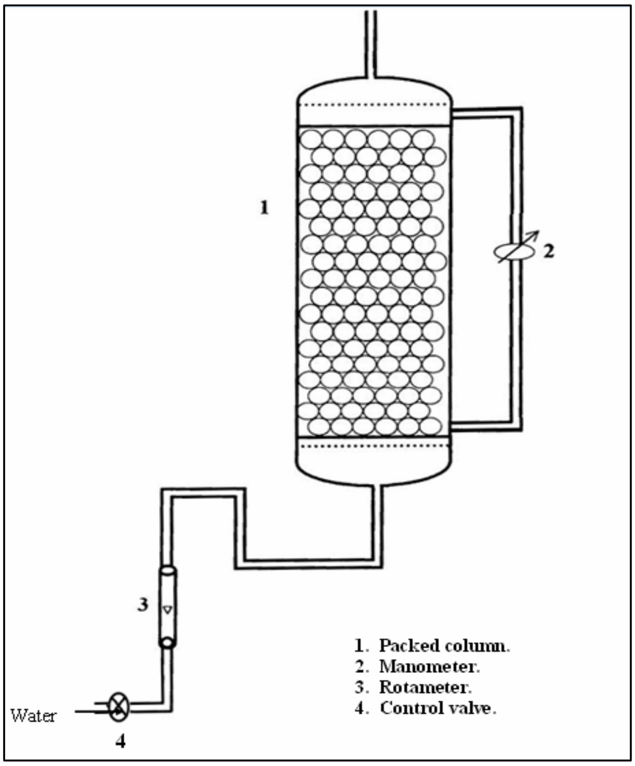


Figure 1 Apparatus diagram

The particles were poured into the column and the bed porosity was determined using the following equation (Geankoplis 2003):

$$\varepsilon = 1 - \frac{\rho_b}{\rho_t} \qquad (3)$$

Where ρ_t is the true density of the particles, (g/cm^3) and ρ_b is the apparent bulk density, (g/cm^3).

Theory of the Model:

The porosity proposed equations model:

The porosity has a great effect on the properties of packed beds. Several attempts were made to simulate the porosity in packed beds (Carman 1937, Coulson 1949, Stanek and Szekely 1973, Standish and Borger 1979, Standish and Mellor 1980, Standish and Leyshon 1981, Standish and Collins 1983, Standish and Yu 1987, Kubo et al. 1987, Yu et al. 1989, Yu and Standish 1991).

Semi-empirical equation was developed in the present work by modifying Furnas equation of porosity (equ. 2) (Furnas 1931). The new forms of the suggested equations of porosity depend on particle diameter (d_p) and bed diameter (D_r). Experimental data were used to get the new forms of porosity. The proposed equations of porosity can be written as follows:

$$e = i_1 + i_2 \left(\frac{d_p}{D_r} \right)^{i_3} \qquad (4)$$

Where i_1, i_2 and i_3 are constants and can be evaluated from experimental data taken from literatures for water flow through packed bed of sphere packing by using statistical fitting.

Results and Discussions:

The present section deals with the results and discussions of the proposed semi-empirical equation for the porosity. These results depend on values of porosities, bed diameters, particles diameters, velocities, bed length and other parameters taken from experimental work. This section also contains the discussions of the proposed equation results, and the comparisons between these results and experimental results taken from documented literatures, as well as comparisons were made between all these results and similar results taken from Furnas equation.

The porosity proposed equation for water flow through porous media

Equation (4) was fitted using 44 experiments obtained from literatures (Chung et al. 2002, Basu et al. 2003, Chopard and Welsh 2003, Britton and Donegan 2003, Back et al. 2004, Kovell and Jordan 2007, Salah 2007, Abd Al-Nabi 2007), in order to calculate the different constants in it. This had been done for water flow through packed bed for mono size spherical packing system. Many types of packing were used in the present work such as Pea Gravel, Marbles, Glass Marbles, Black Marbles, Clear Marbles, Acrylic balls and Glass spheres. The diameters of the packing materials used in this model are from the range of (0.2-8.89) cm, the porosity is from the range of (0.3-0.76), the bed diameters is from the range of (7.62 - 15.24) cm, velocity is from the range of (0.002 - 0.3) m/s, the pressure drop is from the range of (24.9 – 59097) Pa and the height of packing is from the range of (7.62 - 56) cm. So the new proposed model for the porosity for water flow through packed beds of mono size sphere packing was found to be as follows:

$$e = 0.36 + 0.08 \left(\frac{d_p}{D_r} \right)^{0.5} \qquad (5)$$

The correlation coefficient was 0.9662 and the average percentage error was found to be 0.00012% between experimental work and the proposed equation.

Comparisons between proposed equation, Furnas equation and experimental results

Comparisons between the porosity obtained by using the modified equation (equ. 5), the experimental values of the porosity and the porosity obtained by using the Furnas equation (equ. 2), are shown in table 2:

Table (2)**:** The porosity results for water flow through packed bed

Type of packing	**Dr (m)**	**d_p (m)**	**ε (Experiment)**	**ε (Present work)**	**ε Furnas**	**Reference**
Black marbles*	0.0889	0.0191	0.47	0.4022	0.4479	Back et al. 2004
Marbles*	0.1524	0.0127	0.4	0.388	0.4033	Back et al. 2004
Marbles*	0.0889	0.0127	0.4	0.3953	0.4236	Back et al. 2004
Pea gravel**	0.1524	0.0127	0.38	0.388	0.4033	Chung et al 2002
Marbles***	0.1524	0.0127	0.38	0.388	0.4033	Basu et al. 2003
Pea gravel***	0.0889	0.0127	0.38	0.3953	0.4236	Basu et al. 2003
Pea gravel***	0.0889	0.0127	0.38	0.3953	0.4236	Basu et al. 2003
Pea gravel***	0.1524	0.0127	0.38	0.388	0.4033	Basu et al. 2003
Marbles***	0.0889	0.0127	0.38	0.3953	0.4236	Basu et al. 2003
Marbles***	0.1524	0.0127	0.38	0.388	0.4033	Basu et al. 2003
Marbles****	0.0889	0.0127	0.38	0.3953	0.4236	Chopard and Welsh 2003
Pea gravel****	0.0826	0.0127	0.3	0.3964	0.4273	Chopard and Welsh 2003
Pea gravel****	0.0826	0.0127	0.35	0.3964	0.4273	Chopard and Welsh 2003
Pea gravel****	0.0825	0.0026	0.386	0.379	0.3857	Chopard and Welsh 2003
Marbles****	0.0826	0.0127	0.38	0.3964	0.4273	Chopard and Welsh 2003
Marbles****	0.0826	0.0021	0.38	0.3777	0.3838	Chopard and Welsh 2003
Pea gravel****	0.0825	0.003	0.388	0.3802	0.3876	Chopard and Welsh 2003
Acrylic ball *****	0.08	0.0064	0.3571	0.3875	0.402	Britton and Donegan 2003
Acrylic ball *****	0.08	0.0127	0.4028	0.3969	0.429	Britton and Donegan 2003
Acrylic ball *****	0.08	0.0127	0.4028	0.3969	0.429	Britton and Donegan 2003
Glass marbles*****	0.08	0.0127	0.406	0.3969	0.429	Britton and Donegan 2003
Glass marbles*****	0.08	0.0127	0.406	0.3969	0.429	Britton and Donegan 2003
Acrylic ball *****	0.08	0.0127	0.4054	0.3969	0.429	Britton and Donegan 2003
Glass marbles*****	0.08	0.0127	0.406	0.3969	0.429	Britton and Donegan 2003
Marbles*****	0.1524	0.0889	0.4207	0.4269	0.5733	Britton and Donegan 2003
Marbles*****	0.08	0.0127	0.406	0.3969	0.429	Britton and Donegan 2003
Marbles*****	0.0826	0.0127	0.4	0.3964	0.4273	Britton and Donegan 2003
Marbles*****	0.08	0.0127	0.406	0.3969	0.429	Britton and Donegan 2003
Marbles*****	0.1524	0.0127	0.376	0.388	0.4033	Britton and Donegan 2003
Acrylic ball *****	0.08	0.0064	0.3571	0.3875	0.402	Britton and Donegan 2003
Marbles*****	0.1524	0.0127	0.406	0.388	0.4033	Britton and Donegan 2003
Black marbles******	0.1461	0.019	0.41	0.3939	0.4192	Kovell and Jordan 2007
Black marbles******	0.0889	0.019	0.4	0.4022	0.4477	Kovell and Jordan 2007
Black marbles******	0.1461	0.019	0.41	0.3939	0.4192	Kovell and Jordan 2007
Black marbles******	0.0889	0.019	0.4	0.4022	0.4477	Kovell and Jordan 2007
Glass*******	0.0762	0.0042	0.3793	0.3837	0.3937	Salah 2007
Glass*******	0.0762	0.0051	0.4051	0.3856	0.3978	Salah 2007
Glass********	0.0762	0.0061	0.4156	0.3876	0.4022	Abd Al-Nabi 2007
Glass********	0.0762	0.0079	0.4265	0.3907	0.4102	Abd Al-Nabi 2007
Glass********	0.0762	0.0101	0.4321	0.3942	0.4201	Abd Al-Nabi 2007

*Back et al. 2004,
**Chung et al 2002,
***Basu et al. 2003,
****Chopard and Welsh 2003,
*****Britton and Donegan 2003,
******Kovell and Jordan 2007,
*******Salah 2007,
********Abd Al-Nabi 2007.

Table 2 show a very good agreement between the porosity obtained by using the proposed equation and the experimental data, while results from Furnas equation for porosity was far away from the experimental data, this appears clear in the porosity of the marbles, where the experimental porosity was 0.4207 and the porosity obtained from the proposed equation was found to be 0.4269, while the porosity obtained from Furnas equation was 0.5733.

Studying the effect of different parameters on porosity:

The porosity is affected by many variables. The main two are particle diameter and bed diameter. A certain range for each parameter was taken in this study according to the available experimental data from literatures.

Effect of particle diameter on porosity

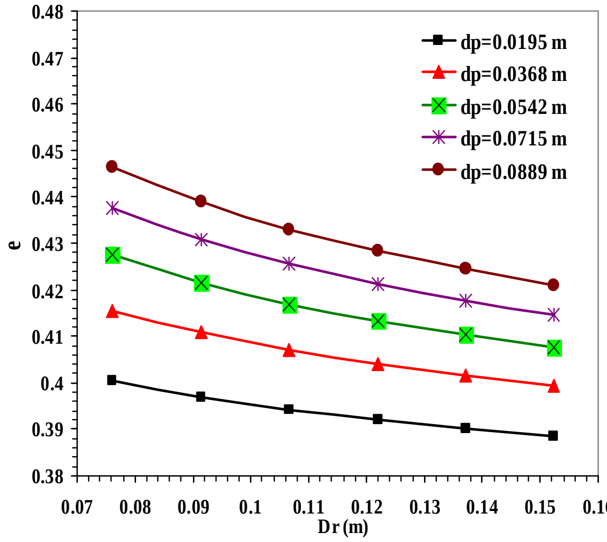
Figure 2 indicates that any increase in the particle diameter causes increase in the bed porosity for the same bed diameter range. For example at bed diameter 0.0762 m, the particle diameter was 0.0195 m and porosity was 0.4, but when the particle diameter was increased to 0.0889 m the porosity increased to 0.446 for the same bed diameter.

Effect of bed diameter on porosity

Figure 3 shows that when the bed diameter was increased the porosity decreased for the same particle diameter. For example when the bed diameter was 0.0914m, the particle diameter was 0.0889m, and the porosity was found to be 0.4388. When the bed diameter increased to 0.1524m the porosity was decreased to 0.4211 for the same particle diameter.

Conclusions

1. The porosity proposed equation results deviate's from experimental results with a very small average percentage error,



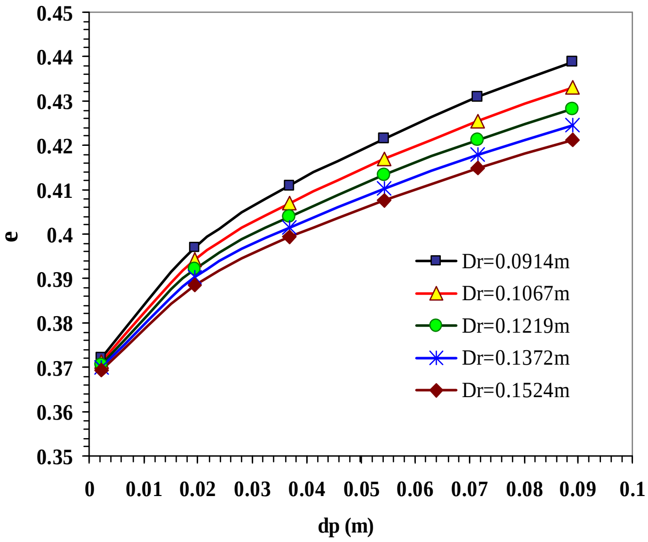


Fig. (3): Porosity versus particle

and they are almost identical, while Furnas equation of porosity was far from the experimental data.

2. The porosity is affected by many variables. The main two are particle diameter and bed diameter, any increase in the particle diameter causes increase in the bed porosity for the same bed diameter range, and whenever the bed diameter was increased the porosity decreased for the same particle diameter.

3. The particle size and size distribution highly affect the bed porosity. For mono size packing, the lower the particle size, the lower is the bed porosity. The porosity value of the multi- size systems are generally less than those of mono

size systems, because the particles of smaller sizes tend to fill the void spaces between the larger sizes particles.

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