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ORIGINAL RESEARCH PAPER

STUDY OF HYDRODYNAMICS IN FIXED BED OF COMPOSITE GRANULAR MATERIALS

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Abstract: This study aims at the experimental determination of pressure drop and friction factor at gas flow through fixed beds of granular silica gel, alumina and activated carbon, and establishment of an equation containing a modified friction factor F_m to calculate pressure drop. In order to calculate the modified friction factor, an equation was suggested.
The experimental values for pressure drop and friction factor were determined using spherical grains of silica gel, cylindrical grains of alumina and silica gel, alumina and activated carbon impregnated with calcium chloride. By means of the suggested equation, the values of pressure drop in fixed bed were calculated and compared with the experimental values. A good agreement between the predicted and experimental data is noticed.

Keywords: *adsorption, fixed bed, friction factor, hydrodynamics, pressure drop*

INTRODUCTION

An important hydrodynamic factor of the fluid flow through a fixed bed is represented by the pressure drop that is a measure of the required energy consumption.
Literature comprises a large number of papers [1 – 15] that refer to the pressure drop and friction factor respectively of fluid flow through a granular fixed bed. The equations established theoretically for determining pressure drop and friction factor, presented in references [1 – 5, 9 – 12] are available for non-porous grains with exterior surface without roughness. In case of fixed bed of porous or rough external surface grains, the pressure drop values calculated with these equations are smaller then those determined experimentally.
This study describes the experimental determination of pressure drop and friction factor at gas (air) flow through granular beds of silica gel-calcium chloride, alumina-calcium chloride and activated carbon-calcium chloride composite materials. It is established a relation to calculate the pressure drop.

ESTABLISHMENT OF AN EQUATION FOR PRESSURE DROP

In order to establish a relationship for pressure drop at gas flow through a granular fixed bed, it can be used the equation:

$$\Delta p = F \cdot \frac{H}{d_e} \cdot \frac{\rho \cdot v_f^2}{2 \cdot \varepsilon^2} \qquad (1)$$

where: F - friction factor; H - fixed bed height; v_f- gas flow rate; ε - fixed bed porosity; d_e - equivalent diameter of the fixed bed.
Equivalent diameter d_e can be expressed by the relationship:

$$d_e = \frac{2 \cdot \varepsilon \cdot \psi \cdot d}{3 \cdot (1-\varepsilon)} \qquad (2)$$

where: d - equivalent diameter grain; ψ - shape factor.
Based on expressions (1) and (2) it can be written:

$$\Delta p = \frac{3 \cdot F}{4} \cdot \frac{H}{\psi \cdot d} \cdot \frac{1-\varepsilon}{\varepsilon^3} \cdot v_f^2 \cdot \rho \qquad (3)$$

Introducing the notation $F_m = 3 \cdot F / 4$, equation (3) becomes:

$$\Delta p = F_m \cdot \frac{H}{\psi \cdot d} \cdot \frac{1-\varepsilon}{\varepsilon^3} \cdot v_f^2 \cdot \rho \qquad (4)$$

where: F_m - modified friction factor.
Relationship (4) allows one to calculate the pressure drop for gas phase flow through granular fixed bed.
To calculate the modified friction factor, F_m, the following relationship is proposed:

$$F_m = a \cdot \mathrm{Re}^{-n} \qquad (5)$$

where: *Re* - Reynolds number $\left(\mathrm{Re} = \frac{\rho \cdot v_f \cdot \psi \cdot d}{\eta}\right)$; *a, n* - parameters that depend on the material nature and shape of grains, and gas flow regime; η - dynamic viscosity of gas phase.

Parameters *a* and *n* can be experimentally determined. When the flow regime is laminar, $n = 1$, and when it is turbulent, $n = 0$.

EXPERIMENTAL

In order to determine experimentally the pressure drop, the laboratory experimental set-up shown in Figure 1 was used.

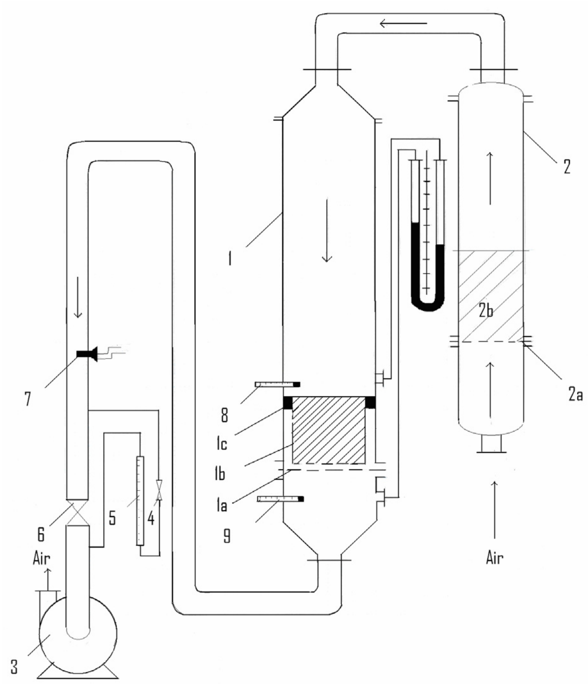

Figure 1. *Experimental set-up:1 - column; 2 - air dryer; 3 - fan; 4, 6 - valves; 5 - flowmeter; 7 - Pitot-Prandtl tube; 8, 9 - thermometers; 10 - manometer.*

The installation consists in two vertical cylindrical columns (1) and (2), a fan (3) and measurement devices for temperature and air flow rate. Column (1) is made of stainless steel and at the column bottom is fixed a metallic sieve (1a) to support the vessel with granular fixed bed (1b). A rubber fitting (1c) was used to seal the space between vessel (1b) and column (1) wall. Column (2) is the air drying chamber and it is made of two cylindrical stainless steel sections fitted by flanges. Between the two sections is fixed a sieve made by stainless steel (2a) to support the adsorbent composite material bed (2b) meant for air drying.

The air flow rate is controlled at low values by means of valve (4) and flowmeter (5), and at high values by means of valve (6) and Pitot-Prandtl tube (7) that is connected to an inclined differential manometer. In the superior section of column (2) is fixed an electrical resistance needed for air heating. Air temperature is controlled by means of an autotransformer and thermometers (8) and (9) fixed at the top and bottom of the fixed bed. The manometer (10) is used to measure the pressure drop of gas flow through the fixed bed.

The experiments were carried out at atmospheric pressure, 303 K temperature and several values of air flow rate ranged between 5.3 and 27.3 $m^3 \cdot h^{-1}$. In the experimental investigations, grains of composite materials (silica gel impregnated with $CaCl_2$ – MCSS1; alumina impregnated with $CaCl_2$ – MCA1; activated carbon impregnated with $CaCl_2$ – MCC1) and the proper basic matrices (silica gel, alumina, activated carbon) were used. The specified materials present spherical shape of 3.57 mm in diameter (silica gel and MCSS1), cylindrical shape having the dimensions d = 3.2 mm, l = 3.2 mm (alumina and MCA1), cylindrical shape having the dimensions d = 3.5 mm, l = 3.5 mm (activated carbon and MCC1). Geometrical parameters of the fixed bed are D = 0.086 m, H = 0.07 m.

RESULTS AND DISCUSSION

Using the laboratory experimental set-up shown in Figure 1, the pressure drop was experimentally determined when the air cross a granular fixed bed of adsorbent material (silica gel, alumina, activated carbon, MCSS1, MCA1, MCC1) for several values of air flow rate ranged between 5.3 and 27.3 $m^3 \cdot h^{-1}$. The results obtained are presented in Table 1.

***Table 1**. Pressure drop variation as a function of air superficial velocity*

M_v [$m^3 \cdot h^{-1}$]	Δp [mm H_2O]					
	Alumina	**MCA1**	**Activated carbon**	**MCC1**	**Silica gel**	**MCSS1**
5.3	4	4.5	2.5	2.5	3.5	4.0
7.2	7	8	4.5	4	6	7.5
9.1	10	11	7.0	7.5	9	12
10.9	13	15.5	9.5	10	12	15
12.8	18.5	20	12	13	16	18
14.5	24	26	16	17	20	25
16.4	30	31,5	20	21	25	32
18.2	35	39	24	26	31	39
20.0	42	46	29	30	35	46
21.8	50	53	33	35	41	54
23.6	56	61	40	41	48	63
25.5	66	69	47	48	54	70
27.3	73	77	53	55	63	78

As can be seen from Table 1, at the flow of air through a fixed bed of adsorbent material, the pressure drop increases for each type of material with the gas flow rate. The lowest values of pressure drop occurs in the case of activated carbon and MCC1 due mainly to bed porosity that is greater then the porosity of other materials, the grains having higher dimensions. Between the composite material and the basic matrices is no significant difference as it concerns the pressure drop, Δp being slightly higher in case of composite materials in comparison with basic matrices. This aspect may be due to the increase of the external surface roughness of grains as a result of basic matrix impregnation with calcium chloride.

Using relation (4) and data in Table 1, the experimental values of the modified friction factor were determined and plotted in $F_m - Re$ type diagrams, Figures 2 – 4. Diagrams in Figures 2 – 4 pinpoint the existence of three areas where the modified friction factor varies as a function of Reynolds number: laminar, intermediate and turbulent. Critical values of Reynolds number that separates these three areas of factor F_m are different as a function of the material nature of grains, and grains shape.

Diagrams in Figures 2 – 4 highlight the F_m factor variation with Reynolds number for each composite material (MCA1, MCC1 and MCSS1).

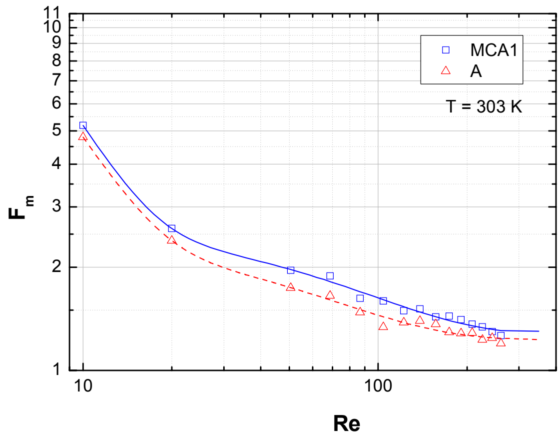

Figure 2. *Variation of modified friction factor as a function of Reynolds number for alumina and MCA1*

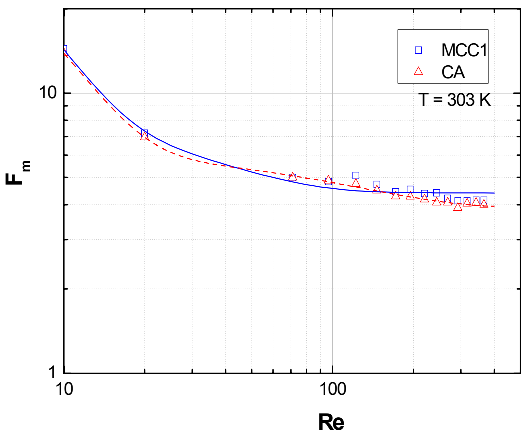

Figure 3. *Variation of modified friction factor as a function of Reynolds number for activated carbon and MCC1*

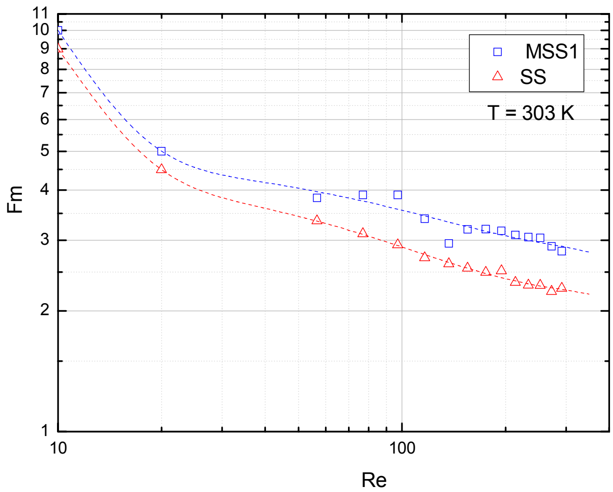

Figure 4. *Variation of modified friction factor as a function of Reynolds number for spherical silica gel and MCSS1*

Further, using relation (5), values of *a* and *n* parameters were calculated as presented in Table 2. As can be noted, the critical values for Reynolds number are higher in case of composite materials MCC1 and activated carbon grains (*Re:* 33, 300). For silica gel grains and MCSS1 material, critical values of Reynolds number are equal to 20 and 215, while in case of alumina and MCA1 grains, the critical values of Reynolds number are equal to 30 and 270.

Table 2. *Values of a and n parameters*

Alumina	Re	< 30	30 – 270	> 270
	a	49.7	20.23	1.22
	n	1	0.59	0
MCA1	Re	< 30	30 – 270	> 270
	a	51.9	7.31	1.28
	n	1	0,33	0
Activated carbon	Re	< 33	33 – 300	> 300
	a	139	6.66	4.05
	n	1	0.07	0
MCC1	Re	< 33	33 – 300	> 300
	a	143.9	10.25	4.14
	n	1	0.23	0
Silica gel	Re	< 20	20 – 215	> 215
	a	89.9	8.44	2.25
	n	1	0.23	0
MCSS1	Re	< 20	20 – 215	> 215
	a	100	10.1	2.80
	n	1	0.22	0

Based on data in Table 2, F_m factor was calculated using relation (5) and then the pressure drop for a granular fixed layer crossed by a gaseous phase (air) was calculated by means of equation (4) at the same values of operating parameters specified in the experimental part. Values calculated for pressure drop are presented in Table 3.

Table 3. *Calculated and experimental values of pressure drop [Pa]*

M_v [$m^3 \cdot h^{-1}$]	v_f [$m \cdot s^{-1}$]	**Alumina**		**MCA1**		**Activated carbon**		**MCC1**		**Silica gel**		**MCSS1**	
		Δp exp.	**Δp (eq. 5)**	**Δp exp.**	**Δp (eq. 5)**	**Δp exp.**	**Δp (eq. 5)**	**Δp exp.**	**Δp (eq. 5)**	**Δp exp.**	**Δp (eq. 5)**	**Δp exp.**	**Δp (eq. 5)**
5.3	0.2533	39.2	44.4	44.1	45.1	24.5	24.2	24.5	25.4	34.3	34.2	39.2	42.5
7.2	0.3441	68.6	69.2	78.4	75.1	44.1	43.7	39.2	44.6	58.8	58.7	73.5	73.4
9.1	0.4349	98	96.3	107.8	111.1	63.7	68.8	73.5	68.7	88.2	88.9	117.6	111.5
10.9	0.5210	127.4	124.2	151.9	150.2	93.1	97.4	98	95.7	117.6	122.4	147	153.6
12.8	0.6108	181.3	155.9	196	196.5	117.6	133.1	127.4	128.9	156.8	163.0	176.4	204.9
14.5	0.6931	235.2	205.5	254.8	242.0	156.8	169.3	166.6	162.1	196	202.9	245	255.3
16.4	0.7839	294	262.9	308.7	297.3	196	216.3	205.8	194.4	245	252.4	313.6	318.0
18.2	0.8699	343	323.8	382.2	353.7	235.2	234.2	254.8	239.4	303.8	303.2	382.2	382.5
20.0	0.9560	411.6	391.1	450.8	410.3	284.2	282.8	294	289.1	343	328.1	450.8	452.5
21.8	1.042	490	464.7	519.4	487.6	323.4	336.0	343	343.5	401.8	389.8	529.2	527.5
23.8	1.128	548.8	544.6	597.8	571.4	392	393.9	401.8	402.7	470.4	456.8	617.4	568.5
25.5	1.218	646.8	635.0	676.2	666.3	460.6	459.2	470.4	469.3	529.2	532.6	686	662.8
27.3	1.304	715.4	727.9	754.6	763.7	519.4	526.2	539	537.9	617.4	610.5	764.4	759.8

In order to verify the equation suggested to calculate the pressure drop, in Table 3 are also shown the experimental data. As can be seen, there is a good agreement between values calculated with relation (4) and experimental ones.

CONCLUSIONS

In this paper, the hydrodynamics of fixed granular beds of composite materials crossed by a gaseous phase is studied.

It was established an equation containing a modified friction factor F_m in order to calculate the pressure drop at gaseous phase flow through a fixed granular bed. For calculating factor F_m, an equation ($F_m = a \cdot Re^{-n}$) with two parameters, *a* and *n*, was proposed.

The experimental values for pressure drop were determined using spherical grains of silica gel, cylindrical grains of alumina and silica gel, alumina and activated carbon impregnated with calcium chloride.

Based on experimental data related to pressure drop, the modified friction factor was determined and, based on this, the *a* and *n* parameters values, from the calculation expression of F_m factor.

Further, using the proposed equation, the values of pressure drop in fixed bed were calculated and compared with the experimental values. It results a good agreement between the predicted and experimental data.

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