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Numerical Simulation of Hydrodynamics parameters of the Packed Columns: Effects of Geometrical Characteristics on Pressure Drop

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Abstract: Structured packings, have found great applications in industries, because of lower pressure drop and higher capacity and efficiency in comparison with random packings and trays. Dry pressure drop is one of the most important parameters in design of structured packed columns. Type of packing and geometrical characteristics such as specific surface area, dimensions and angle of channels and porosity are among the important parameters affecting pressure drop. In the present work, effect of these parameters on pressure drop has been investigated using a computational fluid dynamics approach. For solving the equations, a commercial CFD package, Fluent 6, was used. The results have been compared with experimental data as well as Bravo model and show good agreement. The average relative errors obtained are between 3.3% and 16.1%. From the results it is shown that pressure drop decreases with decreasing specific surface area of the packing, increasing bed porosity, increasing the channel angle with respect to vertical and increasing the channel dimensions. By increasing the channel angle from 45 to 60°, pressure drop decreases by 59.6%. Increasing the bed porosity from 62 to 98% results in 40% decrease in pressure drop. For Flexipak structured packings, a decrease of 49% in specific surface area results in 57.6% decrease in pressure drop.

Key words: Structured packings . packed columns . pressure drop . computational fluid dynamics . CFD

INTRODUCTION

In recent years, the structured packed columns have been widely used in separation processes such as distillation, absorption and extraction. Since the 1960s, structured packings have been applied for contacting the gas and liquid phases in distillation columns. Structured packings are preferred where a high separation performance and low-pressure drop are required [1].

Corrugated sheets packings can be made of plastic or metallic material. Each sheet exists of many triangular channels. By decreasing the channel dimensions, specific surface area of the packings increases. The shapes and dimensions of some structured packings are shown in Fig. 1 [2].

Dry pressure drop is one of the most important parameters that is used for investigation of hydrodynamics characteristic in the packed columns [3]. Type of packing and geometrical characteristics such as specific surface area, dimensions and angle of channels and porosity are among the important parameters affecting pressure drop.

Computational Fluid Dynamics (CFD) is an important tool in design and improvement of the process plants. Using the CFD for design studies reduces the number of necessary experiments and results, which would hardly be accessible by measuring the pressure distribution in the structured packed columns [4, 5].

In the present work, CFD analysis of the gas phase pressure drop in typical structured packings such as Montzpak 250Y, Montzpak 250X, KATAPAK-S, Flexipac1Y, 2Y and 3Y are presented and the results of CFD analysis have been compared with the experimental data and a theoretical model. Geometrical and surface characteristics of these packings are shown in Table 1 [6].

THEORETICAL MODELS

Pressure drop models can be classified into two groups: generalised models (Kister and Sherwood models) and characteristic models [7]. Some of the characteristic models are Bravo model [8], Olujic model [9, 10] and Brunazzi model [11]. In this paper, the Bravo model has been used. The Bravo model for the gas phase pressure drop is expressed as:

$$\left(\frac{\Delta p}{\Delta z}\right)_{dry} = \Psi * \rho_g * U_{ge} / d_{eq} \quad (1)$$

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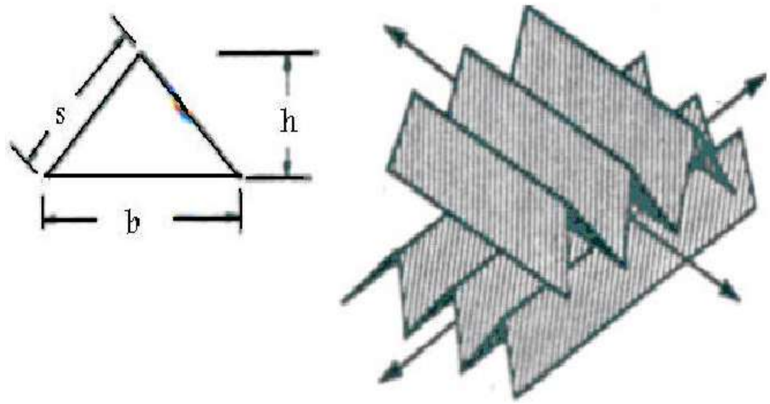

Fig. 1: Dimensions of triangular channels in the structured packings [2]

Table 1: Geometrical and surface characteristics of structured packings [6]

Packing type	$a_p(m^{-1})$	ε(%)	θ(deg)	b(m)	h(m)	s(m)
Montzpak 250Y	244.0	98.0	45	0.0225	0.0120	0.0165
Montzpak 250X	245.0	97.8	60	0.0223	0.0120	0.0165
Flexipak 1Y	453.0	91.0	45	0.0127	0.0064	0.0090
Flexipak 2Y	223.0	95.0	45	0.0255	0.0127	0.0180
Flexipak 3Y	115.0	96.0	45	0.0509	0.0255	0.0360
KATAPAK-S	128.2	62.2	45	0.0218	0.0115	0.0160

Table 2: Values of constants in equation 4 [8]

Packing type	A	B
Montzpak 250Y	0.194	212.90
Montzpak 250X	0.100	54.42
Flexipak	0.171	92.70

Where effective gas velocity and d_{eq} are defined as:

$$U_{ge} = U_{gs}/\varepsilon * \sin\theta \quad (2)$$

$$d_{eq} = S \quad (3)$$

Friction factor can be correlated by the general relationship as:

$$\Psi = A + \left(\frac{B}{Re}\right) \quad (4)$$

Coefficients in equation 4 are shown in Table 2 [10]. The friction factor for KATAPAK-S structured packing can be expressed as [12]:

$$\Psi = 6.275.Re_g^{-0.293}\left\{550\langle Re_g\langle 1550\right\} \quad (5)$$

$$\Psi = 2.564.Re_g^{-0.171}\left\{1550\langle Re_g\langle 6000\right\} \quad (6)$$

Where

$$Re_g = \frac{\rho_g.U_{ge}.S}{\mu_g} \quad (7)$$

Pressure drop per unit of bed length can be obtained from following equation:

$$\left(\frac{\Delta p}{\Delta z}\right) = \Psi * \left(\frac{\rho_g}{S}\right).\left(\frac{U_{gs}}{\varepsilon.\sin\theta}\right) \quad (8)$$

The final correlation can be obtained from combining eqs. 4, 7 and 8 as follow:

$$\left(\frac{\Delta p}{\Delta z}\right)_{dry} = \frac{A.\rho_g}{S.\varepsilon^2.(\sin\theta)^2}.U_{gs}^2 + \frac{B.\mu_g}{S^2.\varepsilon\ \sin\theta}U_{gs} \quad (9)$$

CFD SIMULATION

The general conservation equations describing the gas flow taking place within structured packings consist of the continuity and momentum equations [6].

$$\frac{\partial}{\partial X_i}(\rho U_i) = 0 \quad (10)$$

$$\frac{\partial}{\partial X_j}\left(\rho U_i U_j\right) = -\frac{\partial}{\partial X_i}P + \frac{\partial}{\partial X_j}\tau_{ij} + \frac{\partial}{\partial X_j}\left(-\rho U_i' U_j'\right) + \rho g_i \quad (11)$$

In the above equations, ($-\rho U'_i U'_j$) is the turbulent Reynolds stress and is handled via the boussinesq approximation.

$$\left(-\rho U'_i U'_j\right) = \mu_t\left(\frac{\partial}{\partial X_j}U_i + \frac{\partial}{\partial X_i}U_j\right) - \frac{2\delta_{ij}}{3}\left(\rho.k + \mu_t\frac{\partial}{\partial X_i}U_i\right) \quad (12)$$

The stress tensor τ_{ij}, is expressed as [13]:

$$\tau_{ij} = \mu\left(\frac{\partial}{\partial X_j}U_i + \frac{\partial}{\partial X_i}U_j\right) - \frac{2\delta_{ij}}{3}\left(\mu\frac{\partial}{\partial X_i}U_i\right) \quad (13)$$

In this work, the total pressure drop is assumed to consist of three terms:

$$(\Delta P)_{Total} = \Delta P_1 + \Delta P_2 + \Delta P_3 \quad (14)$$

Where

ΔP_1 is the pressure drop per unit of length of one structured packing sheet.

ΔP_2 is the pressure drop in middle layer.

ΔP_3 is the pressure drop in bed entrance region on first packing layer.

These parameters are shown in Fig. 2.

3-D computational domains for the CFD simulation of gas flow in single structured packing sheet and in the elbow on first layer are shown in Fig. 3. The gas phase was taken to be air with

$$\rho_g = 1.225(kg/m^3), \mu = 1.7894e-5(kg/m.s)$$

and the porosity of the system is $0.622 m^3/m^3$.

For solving the above equations, a commercial CFD package, Fluent 6, was used and mesh preparations were made in Gambit 2.0.4 for structured packing sheets and elbow, unstructured grids were generated. A Dual processor with 6Gb RAM was used. For the gas phase, the low Reynolds K-ε model was used. Each sheet includes eight inlets and eight outlets. At each inlet and at elbow inlet, a specified velocity boundary condition is used and for each outlet, “outflow” boundary condition, is used. At the sheet walls, the “wall boundary condition”, the non-slip condition is used.

SIMULATION RESULTS

CFD is used to calculate the dry pressure drop as a function of gas load factor (F_S) which defined as follows:

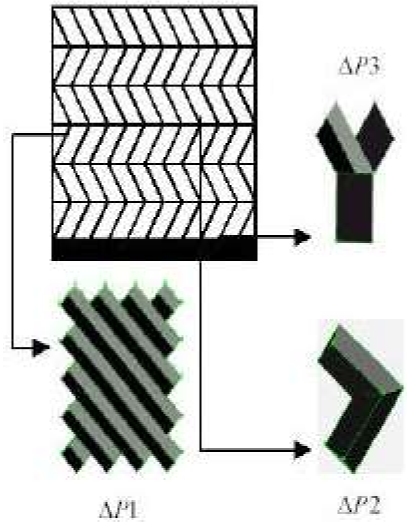

Fig. 2: Various sections in the structured packed columns

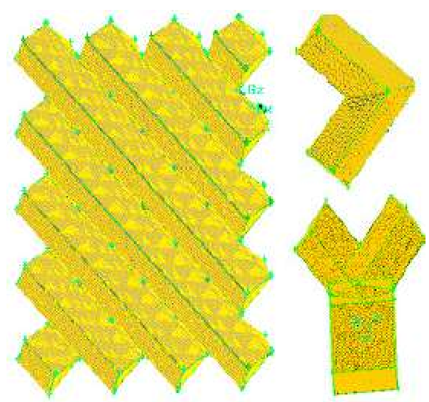

Fig. 3: Computational domains of structured packing by CFD simulation

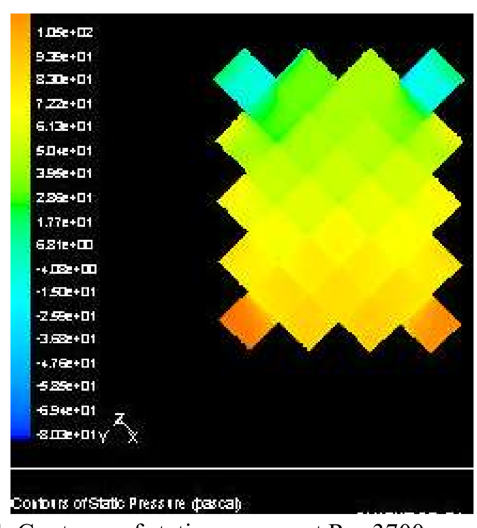

Fig. 4: Contours of static pressure at Re=3700

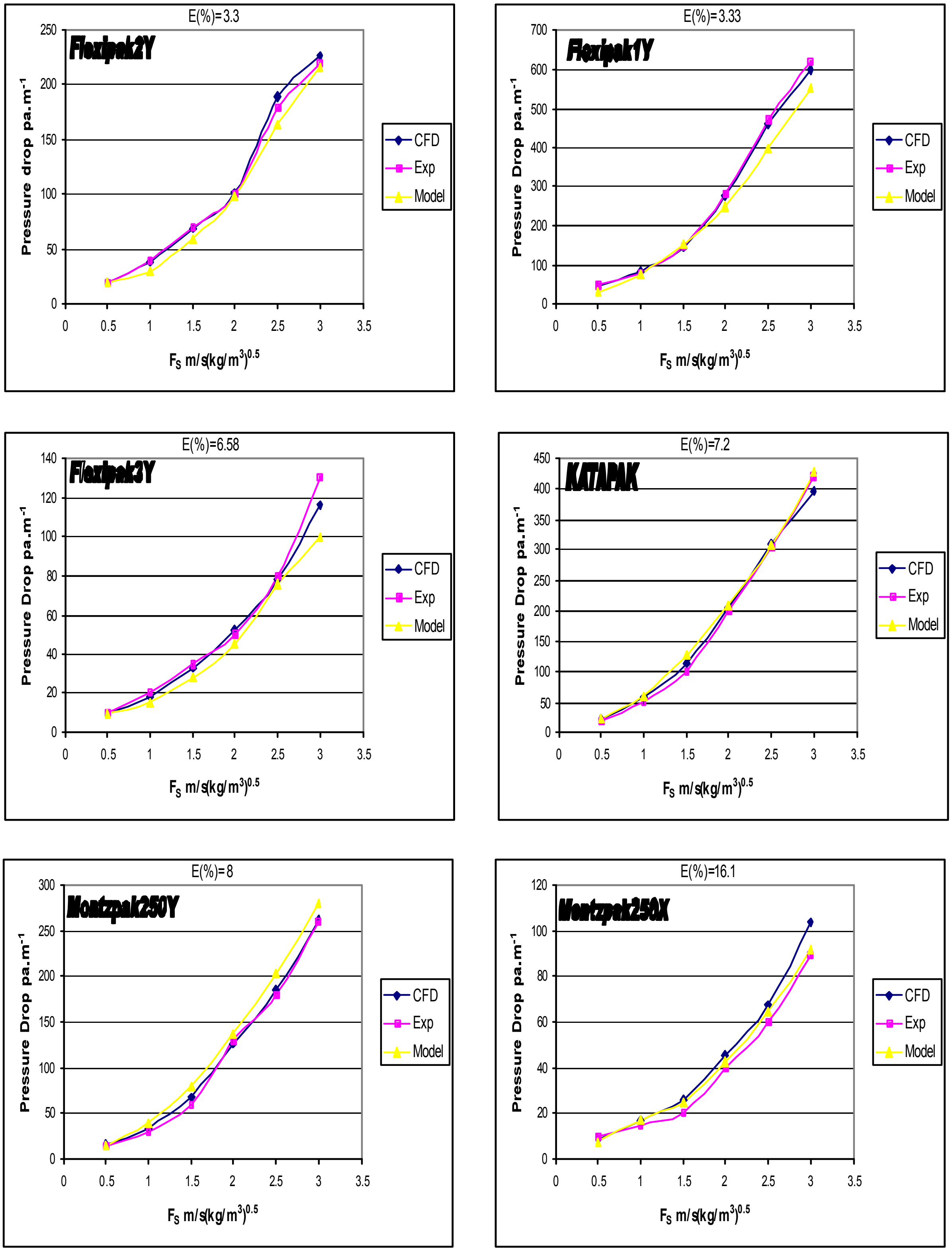

Fig. 5: Pressure drop diagrams for various structured packings

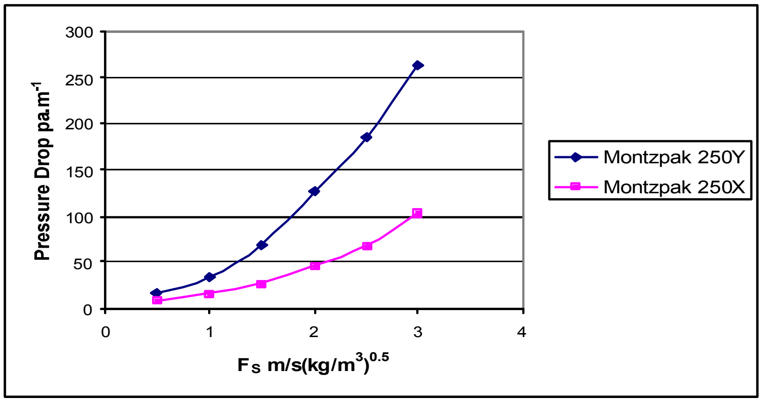

Fig. 6: Effect of corrugation angle on pressure drop in Montzpak250X, Montzpak250Y

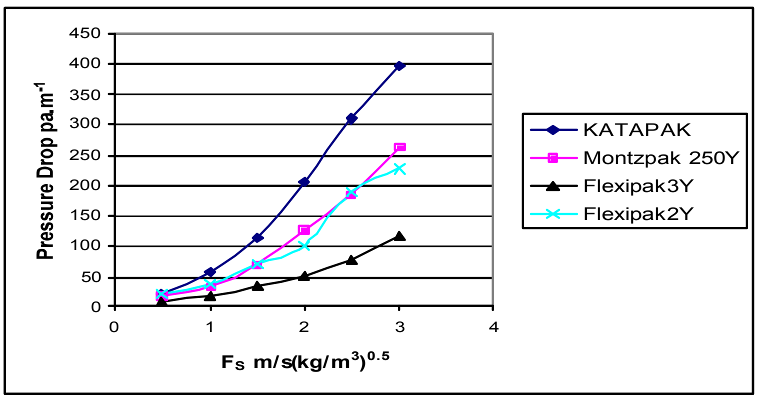

Fig. 7: Effect of porosity on pressure drop

$$F_S = U_{gs}\sqrt{\rho_g} \qquad (15)$$

Contours of static pressure are determined to obtain the dry pressure drop. A sample of Pressure contours at Re=3700 for KATAPAK-S is shown in Fig. 4. Results of CFD analysis are compared with Bravo model [8] and experimental data [12-14], which show a good agreement.

In Fig. 5, total pressure drop is plotted against gas load factor for the packings mentioned earlier. It can be seen that CFD model shows an excellent agreement with the experimental data and Bravo model. The average relative error, which is shown in each diagram, was defined as:

$$E(\%) = 100 * \frac{1}{N}\sum\left|\frac{\left(\frac{\Delta P}{H}\right)_{Exp} - \left(\frac{\Delta P}{H}\right)_{CFD}}{\left(\frac{\Delta P}{H}\right)_{Exp}}\right| \qquad (16)$$

Effect of corrugation angle on pressure drop: Montzpak 250X and Montzpak 250 Y structured packings have been chosen for investigation of corrugation angle effects on pressure drop. These packings have the same specific surface area, but the corrugation angle in Montzpak 250X is 60° and in Montzpak 250Y is 45°. Pressure drop diagram for these packings is shown in Fig. 6. It can be seen from this figure that pressure drop in Montzpak 250Y is higher than Montzpak 250X. For a 60° corrugation angle, flow direction change is 120°, compared to 90° change in 250Y, therefore the flow resistance in Montzpak 250X is much lower than 250Y and pressure drop is approximately 60% lower than Montzpak 250Y.

Effect of porosity on pressure drop: Pressure drop in KATAPAK-S structured packing with 62.2% porosity was compared with the packings with 98% porosity. Figure 7 shows the pressure drop diagram. From this figure, pressure drop in KATAPAK-S is between 40% to 70% higher than other packings. In KATAPAK-S packings, catalyst particles are sandwiched between corrugated sheets, which results in lowering the porosity.

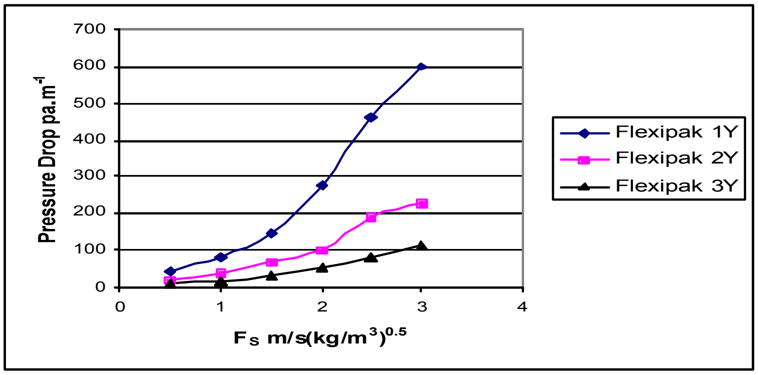

Fig. 8: Effect of specific surface area on pressure drop in Flexipak structured packings

Effect of specific surface area on pressure drop: Dimensions of triangular channels and specific surface area in structured packings are among the important parameters affecting on dry pressure drop. In this section, Flexipak 1Y, 2Y and 3Y with specific surface area 453, 223 and 115(m^{-1}) have been studied. Figure 8 shows the pressure drop diagram for these packings. It is shown that pressure drop in Flexipak 1Y is higher than other packings. Dimensions of triangular channels of this packing are small, therefore specific surface area of this packing is higher than Flexipak 2Y and 3Y. Since the available area for gas flow in this packing is small, the pressure drop is higher than others.

CONCLUSIONS

In this paper, the momentum and continuity equations have been solved using CFD analysis to determine dry pressure drop in the structured packings. Static pressure drop contours of gas flow in the sheet entrance and middle elbows of packings were plotted. Pressure drop in Montzpak 250Y, Flexipak 2Y and Flexipak 3Y are 37, 40 and 72% lower than KATAPAK-S, respectively.

In Montzpak structured packings, by increasing the channel angle from 45° to 60°, pressure drop decreases by 59.6%.

For Flexipak structured packings, a decrease of 49% in specific surface area results in 57.6% decrease in pressure drop.

In Flexipak 3Y with 115m^{-1} specific surface area pressure drop is 83% lower than Flexipak 1Y with 453m^{-1} specific surface area.

In general, it is shown that pressure drop decreases by decreasing specific surface area of the packing, increasing bed porosity, increasing the channel angle with respect to vertical and increasing the channel dimensions.

Nomenclature

A	Constant
a	Specific surface area (m^2/m^3)
B	Constant
b	Channel base (m)
d_h	Hydraulic diameter (m)
E	Average error (%)
F_S	Gas load factor m/s $(kg/m^3)^{.5}$
h	Channel height (m)
K	Wall factor
N	Number of the experiments
P	Pressure (pa)
ΔP	Pressure drop (pa)
Re	Reynolds number
U_{ge}	Effective gas velocity (m/s)
U_{gs}	Superficial gas velocity (m/s)

Greek letters:

θ	Corrugated angle (deg)
ε	Porosity of packing
$\mu_?$	Gas viscosity (kg/m.s)
$\rho_?$	Gas density (kg/m^3)
Ψ	Friction factor

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