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Extended channel model for prediction of the pressure drop in single-phase flow in packed columns☆

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ABSTRACT

This paper introduces a generally valid relationship based on the extended channel model for the prediction of the pressure drop of dry packed bed. The relationship is substantiated by measured values [Maćkowiak, J., 2003, Fluiddynamik von Füllkörpern und Packungen – Grundlagen der Kolonnenauslegung, Springer-Verlag, Berlin] as well as by other literature data for approx. 150 packings of various shapes and sizes of up to 90 mm.

In this work a new method for the determination of the resistance coefficient is presented for application to packings with non-perforated and partially perforated packing wall surface. According to the extended channel model the differences in pressure drop between individual packing shapes can be explained and correlated with new pressure drop equation, which includes a form factor φ as packing parameter. This factor can be easily calculated for simple plain packing shapes and structures and does not require any experimental pressure drop data. Therefore it is possible to predict the dry pressure drop without carrying out any tests for ring- and ball-shaped packings. This model was verified for following types of packing: Pall rings, Bialecki rings, VSP rings, Hiflow rings, I-13 rings, ENVIPAC, Hackette, McPac, R-Pac, SR-Pac and other. In the case of more complicated packing shapes, the form factor φ can be evaluated from experimental dry pressure drop values.

Keywords: Random packing; Hydrodynamics; Dry pressure drop; Channel model; Absorption; Rectification

1. Introduction

It is important to establish the resistance coefficient ψ for exact prediction of pressure drop in the single-phase gas flow through the dumped or structured packing $\Delta p_0/H$ in order to determine the pressure drop in the two-phase counter current flow $\Delta p/H$ as well as the flooding gas velocity $u_{V,Fl}$ in packed columns (Maćkowiak, 2003).

The methods used today to determine the pressure drop of dry dumped and structured packings $\Delta p_0/H$ are derived from the channel model used for pipe flow (Mersmann, 1965, 1988; Barth, 1951; Ergun, 1952; Brauer and Mewes, 1972; Kast, 1964, 1988; Maćkowiak, 1975). The application of this model requires the knowledge of the geometrical parameters of the packing: specific packing surface area a, void fraction ε and wall factor K as well as the operating conditions, factor F_V and the resistance coefficient ψ, which can currently be derived from experimental values only. The resistance coefficient ψ is a function of the shape of individual packing element and can vary with packing diameter (Maćkowiak, 2003).

The range of numerical values for the resistance coefficients ψ for the turbulent gas flow $Re_V \geq 2100$ in packed columns used today was experimentally evaluated (Maćkowiak, 2003) and changes for different packing shown in Fig. 1 in following range:

- $\psi \cong 0.1$–0.3 for tube columns, structured gauze and sheet metal packings;
- $\psi = 0.4$–1 for sheet metal and plastic packings (e.g. Sulzer packing, Ralu-Pak, Montz-Pack and stacked packings);
- $\psi \cong 1$ for metal and plastic packings of a new generation with perforated wall surface (Nor-Pac, Hiflow rings, Envipac, VSP-rings, Ralu-flow, Raschig Super saddles);
- $\psi \cong 1.5$ for ceramic Hiflow rings, R-Pac, SR-Pac, metal McPac and Super Raschig rings;
- $\psi \approx 2$ for metal Top-Pack and VSP-rings;

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Nomenclature

a	specific geometric packing surface area per unit volume (m^2/m^3)
A	total non-perforated wall surface area of a packing element, $A = \pi \cdot d \cdot h$ for ring type of packing (m^2)
A_0	perforated wall surface area of a packing element (m^2)
C_p	constant for Eq. (10c)
d	nominal packing diameter (m)
d_h	hydraulic diameter of packed bed (m)
d_p	particle diameter, $d_p = 6(1-\varepsilon)/a$ (m)
d_S	column or tower diameter (m)
f	function
F_V	gas or vapour capacity factor, $F_V = u_V \cdot \rho_V^{0.5}$ ($Pa^{0.5}$)
h	height of individual packing element (m)
H	height of packed bed (m)
K	wall factor, Eq. (5)
K_A, K_B	constants for Eq. (18) or (19)
$K_1, \ldots, K_4$	constants
l	channel length with non-perforated wall surface area A (m)
l_x	channel length with perforated wall surface area A_0 (m)
p	pressure (bar)
Δp	pressure drop of irrigated packed bed (Pa)
Δp_0	pressure drop of dry packed bed (Pa)
u_V	gas or vapour velocity, based on the cross-sectional area of an empty column (m/s)
$u_{V,Fl}$	gas or vapour velocity, based on the cross-sectional area of an empty column at flooding point (m/s)
$\bar{u}_V$	mean effective gas or vapour velocity (m/s)

Greek letters

α	relative form factor of individual packing
$\delta(\Delta p_0/H)$	relative error, based on experimental value $(\Delta p_0/H)_{exp}$ (%)
ε	void fraction of any type of packing (m^3/m^3)
λ	resistance coefficient, in Eq. (1)
ν_V	kinematic viscosity of gas (m^2/s)
ρ_V	gas density (kg/m^3)
φ	form factor of dry packing, in Eqs. (12) and (16)
ψ	resistance coefficient for single-phase flow through packed bed, in Eq. (7)
ψ_0	resistance coefficient for single-phase flow for classical, non-perforated packing elements such as ceramic Raschig rings, in Eqs. (16) and (19)
ψ^0	resistance coefficient for single-phase flow through packed bed, in Eqs. (10c) and (10d)

Indices

cal	calculated value
exp	experimentally determined value
Fl	at flooding point
met.	metal
V	vapour or gas
i	index: 1,..., n
T	top of the column

Dimensionless numbers

$Re_V = \frac{u_V \cdot d_p}{(1-\varepsilon)\cdot \nu_V} \cdot K$	modified Reynolds number of gas phase, $K \equiv 1$ for structured packing (Maćkowiak, 2003), $K \neq 1$ for random and stacked packing

$\psi \approx 2.42$ for classic packings (Pall rings, Intalox saddles and ceramic Berl saddles);
$\psi \approx 2.62$ for metal Bialecki rings and I-13-rings;
$\psi \cong 3.1$ for ceramic Raschig rings;
$\psi \cong 7.0$ for metal Raschig rings.

According to Maćkowiak (2003), for every type or dimension of packing the resistance factor ψ must be experimentally evaluated and it is not known up today the correlation between the shape of packing and the value of resistance factor ψ.

2. Theoretical principles

2.1. *Literature review*

The pressure drop which affects a gas phase flowing through a packed bed can be expressed by Eq. (1), developed by Darcy and Weißbach (e.g. Barth, 1951; Ergun, 1952; Brauer and Mewes, 1972), used for pipe flow:

$$\frac{\Delta p_0}{H} = \lambda \cdot \frac{\bar{u}_V^2}{2 \cdot d_h} \rho_V \text{ [Pa/m]} \tag{1}$$

The effective gas velocity $\bar{u}_V$ in the packed bed is defined by Eq. (2)

$$\bar{u}_V = \frac{u_V}{\varepsilon} \text{ [m/s]} \tag{2}$$

and the hydraulic diameter d_h of the packing is calculated by Eq. (3) (Brauer and Mewes, 1972)

$$d_h = \frac{2}{3} \cdot \frac{\varepsilon}{1-\varepsilon} \cdot d_p \cdot K \text{ [m]} \tag{3}$$

where d_p is particle diameter and K is the wall factor:

$$d_p = 6 \cdot \frac{1-\varepsilon}{a} \text{ [m]} \tag{4}$$

$$K = \left(1 + \frac{2}{3} \cdot \frac{1}{1-\varepsilon} \cdot \frac{d_P}{d_S}\right)^{-1} \tag{5}$$

According to Maćkowiak (2003), $K \equiv 1$ is valid for structured packings.

The substitution of Eqs. (2) and (3) into Eq. (1) gives the relationship (6)

$$\frac{\Delta p_0}{H} = \lambda \cdot \frac{3}{2} \cdot \frac{1-\varepsilon}{\varepsilon^3} \cdot \frac{u_V^2 \rho_V}{d_p \cdot K} \text{ [Pa/m]} \tag{6}$$

With $(3/2)\lambda = \psi$ and $F_V = u_V \cdot \sqrt{\rho_V}$, we obtain the following Eq. (7) to calculate the pressure drop for single gas flow through the packed bed (Brauer and Mewes, 1972):

$$\frac{\Delta p_0}{H} = \psi \cdot \frac{1-\varepsilon}{\varepsilon^3} \cdot \frac{F_V^2}{d_p \cdot K} \text{ [Pa/m]} \tag{7}$$