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Pressure drop of highly efficient Raschig Super-Ring packing for column apparatuses

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The present work presents and generalizes own experimental data for the pressure drop of highly efficient metal Raschig Super-Ring (RSR) packing for packed columns. The contemporary demands from the chemical industry for environment protection and waste free production lead to focusing on application of these apparatuses in purification of flue gases and waste water. RSR is modern high-performance random packing of latest generation, which combines effective mass transfer, large interfacial area and uniform distribution of the phases over the column cross section. There is no universal methodology for calculating the performance characteristics of this packing. The constants of the existing equations for practical calculations are obtained for each individual packing size. The aim of the present work is to propose more precise equations for prediction of the pressure drop of RSR packing, which are common for all investigated sizes and reflect the influence of the packing geometry and the column redumping.

Keywords: Packed columns; Random packing; Pressure drop; Experiments, Equations for dry and irrigated RSR packing.

INTRODUCTION

Packed bed columns are apparatuses with very large area of application for heat and mass transfer processes in gas-liquid systems. The requirements for industry sustainability lead to their wide employment for solving problems connected with reducing the environmental pollution and increasing the energy efficiency of industrial processes using conventional and renewable energy resources. The development of packings of special materials and designs is of great importance for the modern applications of packed columns.

The present work presents, discusses and generalizes the obtained own experimental data for the pressure drop of metal Raschig Super-Ring (RSR) packing. This is modern high-performance packing introduced in 1995 and classified in [1] as the first random packing of forth generation, which combines effective mass transfer, large interfacial area and uniform distribution of the phases over the column cross section. The high loading capacity and exceptionally low pressure drop, approaching that of structured packings, result in high column throughputs at low operating costs. A comparison with Intalox Metal Tower Packing (IMTP) with the same specific surface area [2] shows that the effective surface of the RSR is about 15 % higher. The advantages of RSR are explained in [1] with the hydrodynamic optimization of the packing geometry. The form of the packing element consisting of sinus strips enables formation of continuous films (characteristic for structured packings). The recurring connection points of the strips promote turbulence. The open geometry provides uninterrupted cleaning of the packing surface preventing from fouling and reduces drops formation, which suppresses foaming. The place of RSR packing is evident from the selection of its industrial applications in [1], which includes Natural gas plant, Methanol plant, Refinery plant, Synthesis gas plant, Effluent water treatment, Effluent gas plant, Sulfur plant, Ammonia plant, Ethanol plant etc.

There is no universal methodology for calculating the performance characteristics of RSR packing. The equations for practical calculations proposed in [3, 4, 5] are obtained on the base of a uniform theoretical approach for random and arranged packings with packing specific constants for each individual packing type and size. A prediction of the pressure drop of RSR packings is presented in [5] with the assumption that the flow through the packing is regarded as a flow through a bundle of identical channels and the relation for an empty tube is applicable. For the pressure drop of dry packing the following equation (in our notation) is proposed:

$$\frac{\Delta P_0}{H} = C_{P,0}\left(\frac{64}{Re_{G1}} + \frac{1.8}{Re_{G1}^{0.08}}\right)\frac{a}{\varepsilon^3}\frac{F_{G1}^2}{2}\frac{1}{K_p}, \qquad (1)$$

where ΔP_0 is dry packing pressure drop, Pa, H is packing height, m; Re_{G1} is gas flow Reynolds number

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$$\mathrm{Re}_{G1} = \frac{w_0 d_{p1}}{(1-\varepsilon)\nu_G}, \tag{2}$$

where w_0 is gas velocity with reference to the column cross section, m^3/m^2s; d_{p1} is particle diameter defined as:

$$d_{p1} = 6\frac{1-\varepsilon}{a}. \tag{3}$$

Here ε is packing void fraction; ν_G is gas phase kinematic viscosity, m^2/s; $F_G = w_0\sqrt{\rho_G}$ is gas velocity factor, $Pa^{0.5}$; ρ_G is gas density, kg/m^3; K_p is wall factor, given by the relation

$$\frac{1}{K_p} = 1 + \frac{2}{3}\frac{1}{1-\varepsilon}\frac{d_{p1}}{d_c}, \tag{4}$$

where d_c is the column diameter, m.

For calculation of the pressure drop under and over the loading point of irrigated packings Billet and Schultes [5] offered the following equation:

$$\frac{\Delta P}{H} = C_{P,0}\left(\frac{64}{Re_{G1}} + \frac{1.8}{Re_{G1}^{0.08}}\right)\left(\frac{\varepsilon - H_t}{\varepsilon}\right)^{1.5}\left(\frac{H_t}{H_{t0}}\right)^{0.3} \times \times \exp\left(\frac{13300}{a^{3/2}\sqrt{Fr_L}}\right) \tag{5}$$

where $Fr_L = \frac{L^2 a}{g}$ is the Froude number; H_{t0} is the total holdup under the loading point m^3/m^3; H_t is the total holdup for the corresponding regime, m^3/m^3; L is the liquid superficial velocity, m^3/m^2s; a is packing specific surface area, m^2/m^3; g is acceleration of gravity, m/s^2.

The packing specific constant $C_{P,0}$, has been obtained by processing experimental data, including data for 6 metal and plastic RSR packings, and the constant's values are given in [5] for each packing type and size.

The aim of the present study is on the basis of own experimental data to propose general equations for calculation of the pressure drop of metal Raschig Super-Ring packings, which are common for all investigated sizes shown in Table 1 and reflect the influence of the packing geometry and the column redumping.

EXPERIMENTAL

The experimental data are obtained in a column of a 470 mm diameter with a system air-water, scheme presented in [6]. The liquid superficial velocity varies between 0 and 120 $m^3/(m^2h)$. The packing height is 2400 mm. The liquid phase packing pressure drop was measured by means of an optical differential manometer with an accuracy of 0.1 Pa. The distributor ensures 923 drip points per m^2. At a pressure drop higher than 200 Pa, a conventional U-tube differential manometer was used. The investigated packing is shown in Fig. 1, [7]. It can be seen that there are three packing geometries differing in number of strips and undulation pattern.

Fig. 1. Metal Raschig Super-Ring packings, source [7]

The packing geometrical characteristics are shown in Table 1. Here h_s denotes the strip width in m, and h- the height of the packing element, m, Fig. 2.

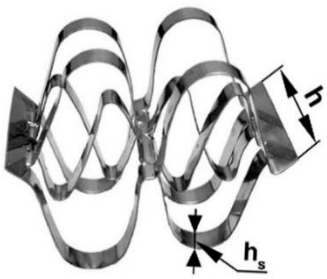

Fig. 2. RSR packing element

The nominal diameter d_n is the diameter of the inscribed circle in the packing element in m. All other geometrical characteristics are defined as averages obtained from triplicate redumping of the packing in the column.

Figs. 3 to 9 present our experimental results for the pressure drop of all investigated packings at different liquid superficial velocities versus the gas velocity factor F_G. The obtained lines are typical for random packings. They are in good agreement with the data of the manufacturer Rraschig GmbH [7] for close values of column diameters. It is shown in [1] that the pressure drop of RSR is lower compared to similar sizes of other high performance packings, e.g. the pressure drop of RSR No. 2 is 38% of the pressure drop of 50-mm Pall-ring, (system cyclohexane/ *n*-heptane, 1.65 bar, total reflux).

Table 1. Geometrical characteristics of the investigated metal RSR packing

Name	Surface area	Free volume	Element height	Number of strips	Strip width	Diameter of inscribed circle	Hydraulic Diameter
	a m^2/m^3	ε%	h mm	n	h_s mm	d_n mm	d_h mm
Raschig Super-Ring No. 0.5	236.2	96.5	15	4	3.8	21	16.3
Raschig Super-Ring No. 0.6	180.5	97.5	20	6	3.3	27	21.6
Raschig Super-Ring No. 0.7	175.9	97.7	20	5	4.0	34	22.2
Raschig Super-Ring No.1	155.5	98.0	25	6	4.2	34	25.2
Raschig Super-Ring No. 1.5	105.8	97.9	30	5	6.0	48	37.0
Raschig Super-Ring No. 2	100.6	98.0	38	6	6.3	50	39.0
Raschig Super-Ring No. 3	74.9	98.0	50	6	8.3	65	52.3

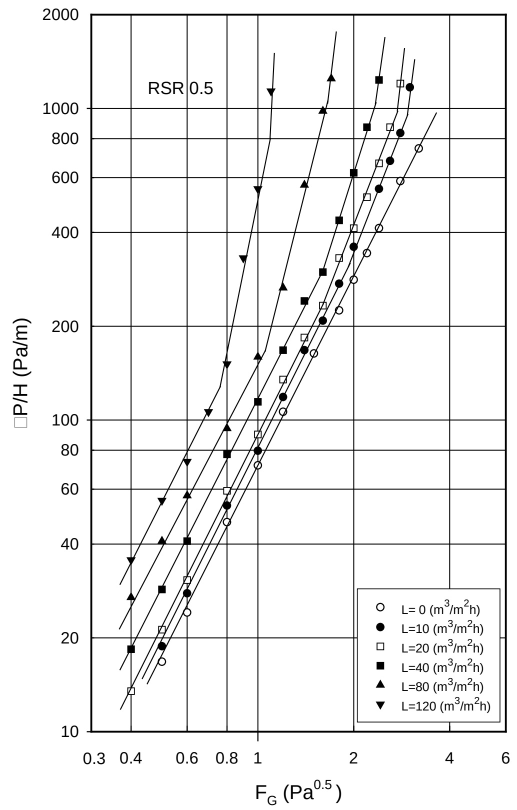

Fig. 3. Pressure drop of metal RSR 0.5 at various superficial liquid velocities vs. gas velocity factor.

It was found in [6] that at comparable values of the specific area and the liquid superficial velocities RSR juxtaposed to IMTP, have about 15% higher effective area and over 35 % lower pressure drop versus effective area, at the same gas velocity.

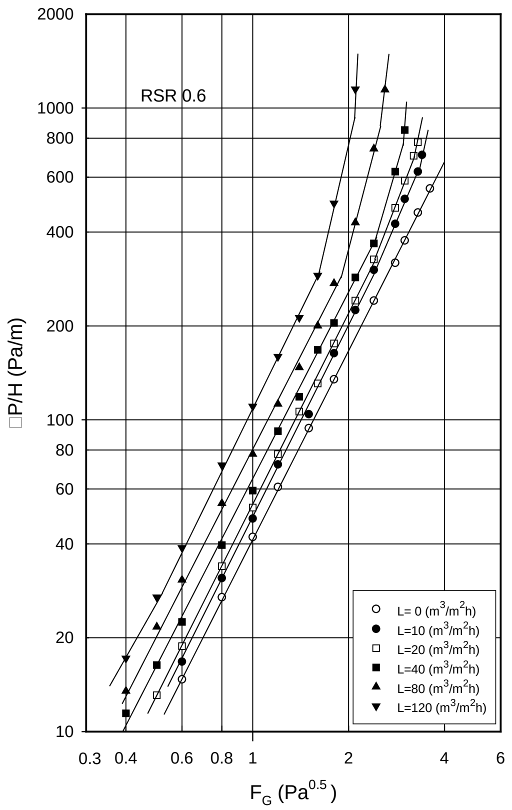

Fig. 4. Pressure drop of metal RSR 0.6 at various superficial liquid velocities vs. gas velocity factor.

EQUATIONS

The present work accepts the usual channel model for the flow through the packing, where H is the height and d_h the diameter of the hypothetical vertical channels and therefore the relation for the dry packing pressure drop is:

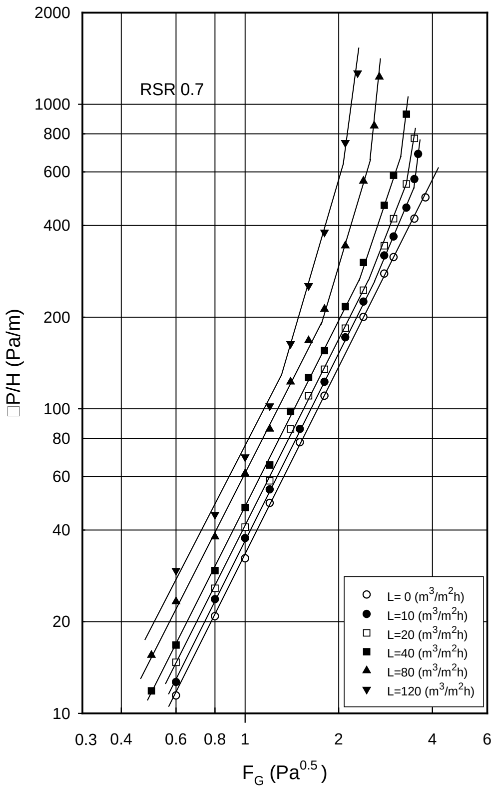

Fig. 5. Pressure drop of metal RSR 0.7 at various superficial liquid velocities vs. gas velocity factor.

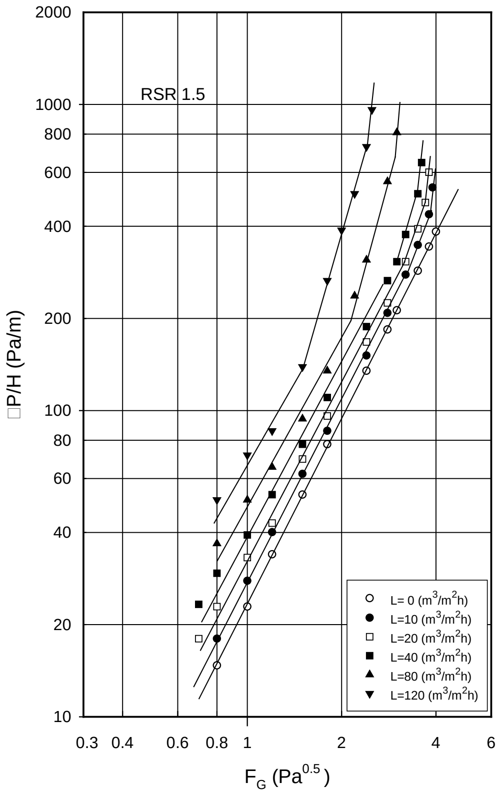

Fig. 7. Pressure drop of metal RSR 1.5 at various superficial liquid velocities vs. gas velocity factor.

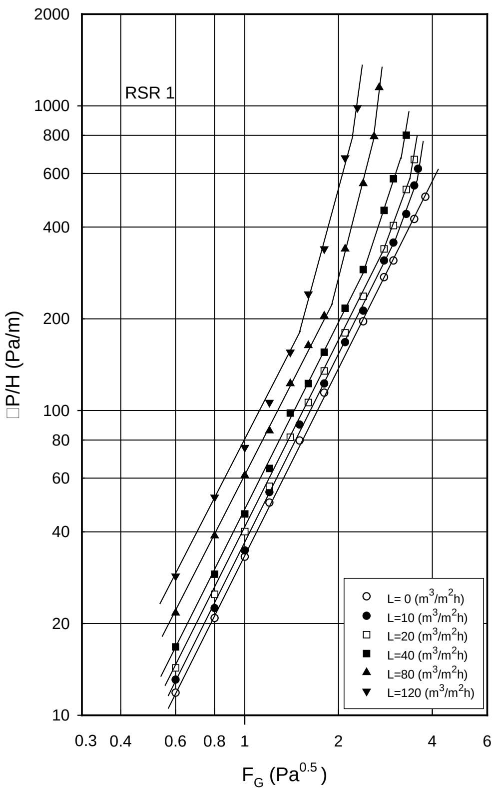

Fig. 6. Pressure drop of metal RSR 1 at various superficial liquid velocities vs. gas velocity factor

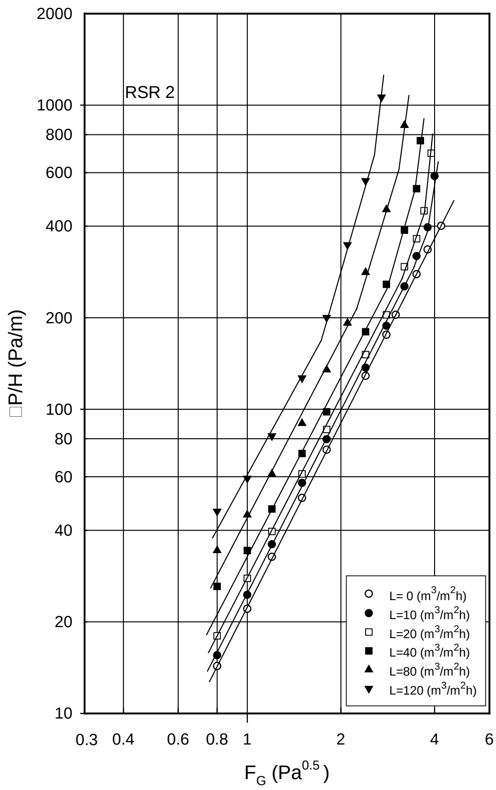

Fig. 8. Pressure drop of metal RSR 2 at various superficial liquid velocities vs. gas velocity factor.

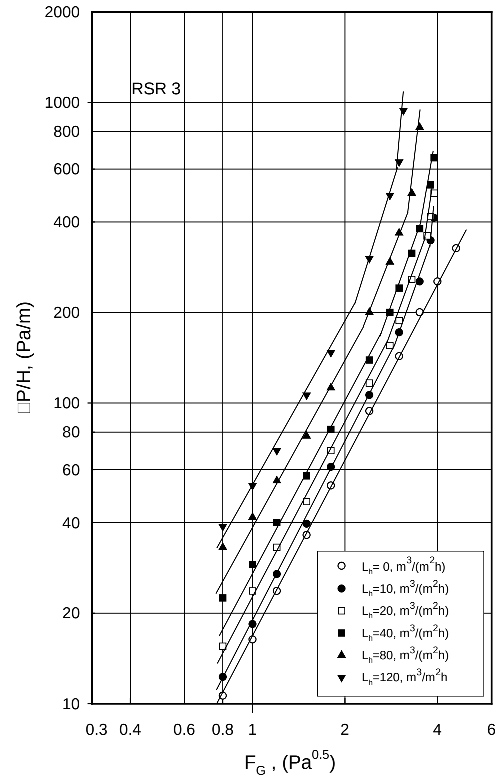

Fig. 9. Pressure drop of metal RSR 3 at various superficial liquid velocities vs. gas velocity factor.

$$\frac{\Delta P_0}{H} = \psi \frac{\rho_G (w_0 / \varepsilon)^2}{2d_h}, \tag{6}$$

where $\psi = \dfrac{\Delta P_0 d_h}{2H\rho_G (w_0 / \varepsilon)^2}$ is the resistance factor, equivalent to Euler number, ΔP_0 is dry packing pressure drop, Pa; $d_h = \frac{4\varepsilon}{a}$ is packing hydraulic diameter, m.

On the basis of dimensional analysis and processing the experimental data for dry packings by regression analysis, the following equation was obtained:

$$\psi = 4.0\left(\frac{h_s}{d_n}\right)^{0.72} (ad_n)^{-0.48} \tag{7}$$

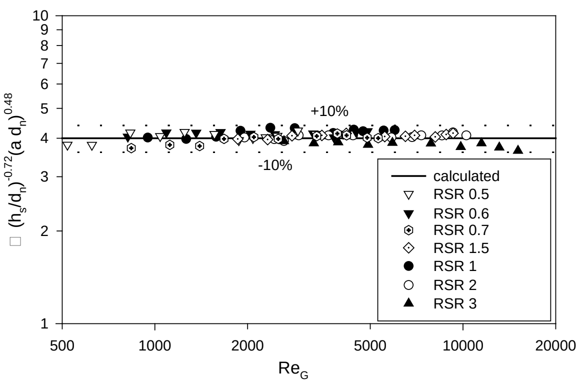

Fig. 10. Comparison of experimental data for dry packings with results calculated by Eq. (7).

Fig. 10 presents a comparison of Equation (7) with the data obtained for all the studied packings, where $\mathrm{Re}_G = \dfrac{w_0 d_h}{\nu_G \varepsilon}$ is Reynolds number for the gas phase.

The mean deviation of Equation (7) is 4.1%. The precision of the obtained experimental constants at 95% statistical reliability is given below:

4.0 ± 0.46; 0.72 ± 0.028; -0.48 ± 0.075.

It was found that the resistance factor depends on the geometrical characteristics of the packing elements expressed by the simplexes h_s/d_n and ad_n, and is independent of Re_G, which speaks for turbulent hydrodynamic regime of the gas flow in the dry packing bed [8]. The range of Re_G in Fig. 10 exhibits some lower limit of the fully developed turbulent regime than that defined in [9] as Re_G>1200, which confirms again that the form of RSR promotes turbulence, [1].

The equations for determination of the irrigated packing pressure drop under and over the loading point are obtained using the relation proposed by Zhavoronkov et al. [10]:

$$\Delta P = \frac{\Delta P_0}{(1 - A)^3} \tag{8}$$

where A is a dimensionless value related to the liquid holdup and represents the packing void fraction occupied by the liquid phase. In [10, 11] it is presented as a sum:

$$A = A_0 + \Delta A \tag{9}$$

A_0 is the value of A under the loading point and ΔA - the increasing of A over the loading point.

Applying dimensional analysis and processing the experimental data for packing pressure drop below the loading point with regression analysis the following expression was obtained:

$$A_0 = 0.26\,\mathrm{Re}_L^{\ 0.17}\, Fr_L^{\ 0.27}, \tag{10}$$

where $Re_L = \frac{4L}{a\nu_L}$ is Reynolds number for the liquid phase; $Fr_L = \frac{L^2.a}{g}$ is Froude number for the liquid phase; ν_L is liquid phase kinematic viscosity, m^2/s.

The mean deviation of Equation (10) is 9.3%. The precision of the obtained experimental constants at 95% statistical reliability is given below:

0.26 ± 0.051; 0.17 ± 0.024; 0.27 ± 0.015.

For the experimental data for packing pressure drop over the loading point the following equation was obtained:

$$\Delta A_0 = 0.17\, Fr_L^{\ 0.30} \left(\frac{w_0^{\ 2}}{\varepsilon^2 g d_h}\right)^{0.30} \tag{11}$$

The mean deviation of Equation (11) is 28%. This value is acceptable because it corresponds to only 8.9% mean deviation of ΔP. The precision of the obtained experimental constants at 95% statistical reliability is given below:

0.17 ± 0.040; 0.30 ± 0.040; 0.30 ± 0.110.

Fig. 11 shows the good agreement of the predicted pressure drop of irrigated packing by using Eqs. (8) to (11) with our experimental data below and over the loading point in the film regime and the loading regime according to the definitions in [11].

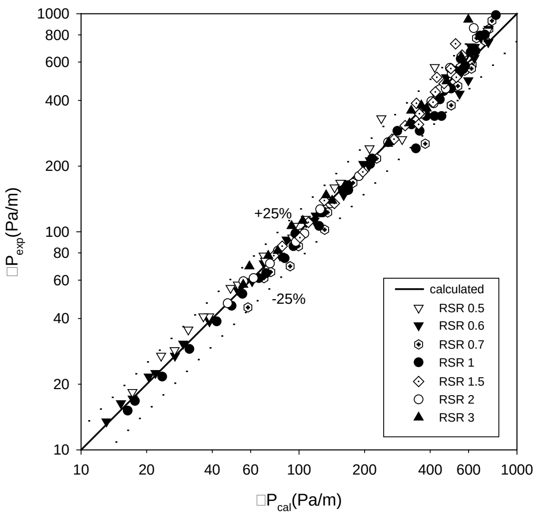

Fig. 11. Comparison of the experimental data for the pressure drop of irrigated packings below and above the loading point with the results calculated by Eqs. (8) to (11).

CONCLUSION

The experimental data for the packing pressure drop obtained by the presented investigation have proven the qualities and advantages of RSR packing. Equations have been proposed, which generalize our pressure drop data from 7 sizes of metal RSR packing and constitute simple and sufficiently precise mathematical model for pressure drop prediction for engineering purposes. Equation (7) is in good agreement with our measurements for the pressure drop of dry packing with mean deviation of 4.1%, and the resistance factor is independent of Re_G, which speaks for turbulent gas flow in the column. The equations for the pressure drop of irrigated packing describe well our experimental data under and over the loading point with mean deviation of 8.9% in respect to the pressure drop.

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ХИДРАВЛИЧНО СЪПРОТИВЛЕНИЕ НА ВИСОКОЕФЕКТИВНИЯ ПЪЛНЕЖ RASCHIG SUPER-RING ЗА КОЛОННИ АПАРАТИ

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(Резюме)

В настоящата работа са представени и обобщени собствени експериментални данни за хидравличното съпротивление на високо ефективен метален пълнеж Raschig Super-Ring (RSR) за колони с пълнеж. Съвременните изисквания към химическата промишленост за опазване на околната среда и безотпадно производство, водят до засилване на интереса към тези апарати за цели като пречистване на димни газове и отпадни води. RSR е модерен високоефективен насипен пълнеж от последно поколение, който съчетава ефективен масообмен, голяма междуфазна повърхност и равномерно разпределение на фазите по напречно сечение на апарата. Не съществува универсална методика за пресмятане на работните характеристики на тези пълнежи. Съществуващите уравнения съдържат константи, определени за всеки отделен размер. Целта на настоящата работа е да се получат по-точни уравнения за пресмятане на хидравличното съпротивление на пълнеж RSR, общи за всички размери, които да отразяват геометрията на пълнежа и презареждането на колоната.