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Horizontal expanded metal sheet packing (Holpack) for mass and heat transfer processes in column apparatuses – study of research, mathematical modeling and industrial application

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The horizontal expanded metal sheet packing is designed and investigated for carrying out mass and heat transfer processes in column apparatuses. The packing is made of expanded metal sheets, placed horizontally on certain distance from one another along the column height. This construction creates conditions for highly effective heat and mass transfer at comparatively low gas pressure drop. This packing has low specific weight and specific effective packing surface area, significantly larger than its specific geometric one.

The present study article is an overview of the most important results regarding the development and investigation of the packing giving all necessary information for its application. The packing is studied in detail; mathematical models and dimensioning methodology of apparatuses are provided and tested. As a result, the packing was successfully implemented in many processes in the chemical and power industry, as well as in the environmental protection. On this base analysis is made and opportunities for its further improvement are discussed. The configuration of the sheets could be improved in order to intensify the mass and heat transfer processes without increasing the pressure drop.

Keywords: Horizontal expanded metal sheet packing, Holpack packing, Packed columns, Pressure drop, Mass transfer, Direct contact heat transfer, Process intensification

INTRODUCTION

The horizontal metal sheet packing is a physical realization of the patented method for performing of mass transfer processes [1]. It is made of expanded metal sheets, placed horizontally on a certain distance along the column height. The sheets are produced on a die by shearing with specially formed knives and subsequent sheet extension, whereupon staggered openings with inclined walls are formed. This product is standardized and is applied for many purposes; if made by thicker metal sheet it usually is used for production of stairs and platforms on different equipments. At first the packing was known as “Horizontal sheet packing”, but later for the sake of convenience it was called “Holpack”.

The investigations carried out confirmed its very good hydrodynamic and mass transfer characteristics. The favorable indicators of Holpack packing made it tempting to use in a large number of technological processes where it found industrial application,

The aim of this study article is to present the most important performance characteristics of the packing, mathematical models and dimensioning methodology, as well as the industrial application in various mass and heat transfer processes. Most of the characteristics are compared to those of some modern highly effective packings. For the industrial design of the apparatuses different models are used depending on the process specific conditions, e.g., the piston flow (plug-flow) model [2] and the dispersion model [3-5].

The results of the research and the experience of the implementation of many years created preconditions for improvement of the packing towards further intensification of processes and equipment. The possible ways of such improvement are also commented.

PRINCIPLES OF THE PACKING DESIGN, MAIN GEOMETRIC AND HYDRODYNAMIC DIMENSIONS

Amongst the known heat and mass transfer apparatuses the hollow irrigated scrubbers are distinguished by the lowest, near to zero pressure drop. However, they are low-effective because of the non-uniform distribution of the gas across the apparatus cross-section and the low values of the mass transfer coefficients. This is due to the absence of elements/structures in which the liquid phase to be hit and turbulized while interchanging its phase surface. A comparison between the hollow irrigated scrubbers and packed columns shows that the latter avoid the disadvantages of the hollow scrubbers at the expense of a significant increase of the apparatus

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pressure drop. Consequently, the development of a hybrid apparatus combining a high mass transfer coefficient and uniform gas velocity distribution in the column with a pressure drop close to that of the hollow irrigated scrubbers appears to be an attractive task.

One convenient solution of this task is replacing the packing by horizontal perforated sheets with large free section, situated horizontally at a distance between them of a few centimeters [1, 6]. The additional pressure drop of the sheets improves the radial uniformity of the gas flow velocity profile. At the same time, the hit of the liquid upon the sheets contributes to the liquid phase turbulization and surface renewal [3, 7-9]. The contradiction between the need of large free section for low gas pressure drop and possibly larger sheet surface, where the irrigating liquid to be hit, can be solved through appropriate sheet profile and packing geometry optimization. Particularly suitable for design of such packing is the material known as "expanded metal sheet" (Figure 1). A good presentation of the technology of its production is given in [10]. It is prevalent for building of factory platforms and stairs, as well as some plate columns constructions. As a very popular manufacturing article it is standardized (e.g., GOST 8706-78). The high productivity of the machines for expanded metal sheets production, the lack of waste of material (like many new metal packings) and the significant (up to 75 %) lengthening of the sheets during its processing to expanded metal sheet determine its low cost. The expanded metal sheets are also used to produce some corrugated structured packings, e.g., Montz packing type BSH [11], Rib mesh packing type BSH [12].

An essential advantage of this type of sheets is the flow directing action of the inclined lamellae forming the slits. They orientate the gas at an angle towards the sheet cross-section contributing to its radial redistribution. This slope also leads to an increased liquid spreading which is favorable for the simplification of the commonly used multipoint liquid distributors. To avoid the one-sided direction of the liquid by the lamellae forming each sheet, the sheets are arranged one above another by rotating at 90° in the same direction – the so called "crosswise" arrangement. Thus, at every fourth sheet the orientation of the lamellae is the same. The distance between the sheets is kept by vertical distancing strips. For comparison, another configuration called "opposite" arrangement rotating the sheets at 180° was also investigated but has not found industrial application due to its lower efficiency. So created packing is mounted in column sections as illustrated by a top-view photograph in Figure 2.

The most important hydrodynamic dimensions of the packing can be determined from its geometric sizes using the following equations (see Figure 1):

$$d_h = \frac{s(B+4A)}{8X+B} \quad a = \frac{8X(s_1/2+\delta)+B(s_1+\delta)}{BC(h_1+h_2)} \tag{1}$$

$$\varepsilon_1 = 1 - \frac{2\delta(B/4+2X)}{BC}$$

where the subsidiary parameter X is determined as follows:

$$X = \frac{1}{2}\sqrt{s^2 + \left(A - \frac{B}{4}\right)^2}\,. \tag{1-a}$$

For comparison with other packings the Holpack void fraction (free packing volume) can be determined:

$$\varepsilon = \frac{\varepsilon_1 h_1 + h_2}{h_1 + h_2}\,. \tag{1-b}$$

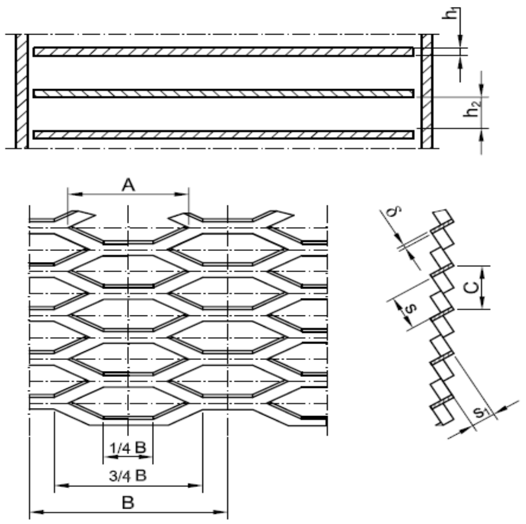


Fig. 1. Packing sheet made of expanded section from metal sheet with main dimensions

Fig. 2. Photograph of a column with Holpack packing

According to this parameter (for example, from Table 1), for the packing No. 6 with one of the lowest sheet free cross-section $\varepsilon_1 = 0.80$ the void fraction is $\varepsilon = 0.974$ and for No. 26 with maximum $\varepsilon_1 = 0.96$ it is $\varepsilon = 0.985$. In both packings the distance between the sheets is equal ($h_2 = 20$ mm). Hence, the void fraction of the Holpack packing is very large (mainly due to the empty volume between the sheets) which is a good precondition for low pressure drop.

For implementing this packing into practice, a thorough research was needed to be accomplished with a view to the most appropriate cases for its use, as well as for collecting data and working out equations for determination of its main characteristics included in the corresponding mathematical models. Such are pressure drop, loading point, liquid hold-up, liquid and gas distribution across the column cross-section, effective specific surface area, axial mixing of the phases, and coefficients of mass transfer, controlled by gas and liquid boundary layer. Only such detailed investigations can be of use for dimensioning of industrial equipment for every specific case. In this way the expedience of using the packing in each heat and mass transfer process at minimal expenses can be estimated.

For the results from the pilot study to be transferrable to industrial objects, the geometric dimensions of the investigated packings and the physicochemical properties of the flowing liquid must vary in a sufficiently wide range. Moreover, it is necessary to verify the influence of the column diameter on the results. On this basis, fundamental research of Holpack packing was carried out at the following limits of the geometric sizes (see Tables 1 to 3) and physical parameters of the liquid phase: L_0 - density of irrigation ($1.5\times10^{-3} \div 6.6\times10^{-2}$ m^3/m^2.s); ρ_L - liquid density (1000 ÷ 1230 kg/m^3), ν_L -liquid kinematic viscosity ($4.0\times10^{-7} \div 1.5\times10^{-6}$ m^2/s). As gas phase air was used. The main characteristics and symbols of the investigated packings are given in Tables 1-3. Further, all symbols which differ, will be noted in the figures themselves.

Table 1. Main characteristics of Holpack packings, used at the research of pressure drop and the mass transfer coefficients, as well as implemented at industrial applications

No.	Sym-bol	A mm	B mm	C mm	δ mm	s mm	s_1 mm	h_1 mm	h_2 mm	d_h mm	ε_1 %	a m^2/m^3	D_c mm
1	○	22.2	30.7	6.4	0.8	5.0	4.0	3.0	5	6.5	81.3	202	190
2	●	22.2	30.7	6.4	0.8	5.0	4.0	3.0	10	6.5	81.3	125	190
3	△	22.2	30.7	6.4	0.8	5.0	4.0	3.0	20	6.5	81.3	70.0	190
4	▲	22.2	30.7	6.4	0.8	5.0	4.0	3.0	40	6.5	81.3	38.0	190
5	×	22.2	30.7	6.4	0.8	5.0	4.0	3.0	20	6.5	81.3	70.0	470
6	⊙	22.2	30.7	6.4	0.8	5.0	4.0	3.0	20	6.5	80.0	70.0	190
7	◒	22.2	30.7	6.4	0.8	5.0	4.0	3.0	20	6.5	80.0	70.0	190
8	◒	22.2	30.7	6.4	0.8	5.0	4.0	3.0	20	6.5	80.0	70.0	190
9	⨁	22.2	30.7	6.4	0.8	5.0	4.0	3.0	20	6 .5	80.0	70.0	190
10	◑	22.2	30.7	6.4	0.8	5.0	4.0	3.0	20	6.5	80.0	70.0	190
11	◐	22.2	30.7	6.4	0.8	5.0	4.0	3.0	20	6.5	80.0	70.0	190
12	●	22.2	30.7	6.4	0.8	5.0	4.0	3.0	40	6.5	80.0	38.0	190
13	□	22.2	30.7	6.4	0.8	5.0	4.0	3.0	40	6.5	81.3	38.0	190
14	◇	22.2	30.7	6.4	0.8	5.0	4.0	3.0	10	6.5	81.3	125	190
15	⊕	22.2	42.7	7.7	1.0	4.5	6.2	4.6	20	6.5	86.0	63.0	190
16	▽	85.0	114	36.0	4.0	16.0	24.0	17.5	0	20.8	83.0	96.7	470
17	■	85.0	114	36.0	4.0	16.0	24.0	17.5	10	20.8	83.0	61.6	470
18	▼	85.0	114	36.0	4.0	16.0	24.0	17.5	50	20.8	83.0	25.1	470
19	●	90.0	121	27.0	1.5	13.0	16.5	13.2	15	17.0	91.6	49.5	190
20	●	90.0	121	27.0	1.5	13.0	16.5	13.2	50	17.0	91.6	22.0	470
21		22.2	30.7	6.4	0.8	5.0	4.0	3.0	50	6.5	81.3	31.0	470
22		90.0	122	23.8	3.0	13.0	13.0	11.0	50	17.0	81.0	24.0	470
23		82.0	109	28.0	1.0	18.3	18.3	14.3	20	23.5	95.0	42.0	800
24		72.0	124	18.5	1.5	15.0	15.0	13.0	50	21.0	90.2	25.0	400, 800, 1200
25		19.0	27.0	7.7	0.6	5.3	4.2	3.5	20	6.8	88.4	56.0	207
26		92.0	120	32.0	0.8	20.0	20.0	13.2	20	25.6	96.0	41.6	207-800

For packings Nos. 1-4 – the packing sheets are rotated at 180^0 to one another. Nos. 6 – 12 – the sheets are covered with polyethylene. Nos. 7 – 11 – the irrigation density varies from 1120 to 1230 kg/m^3 and dynamic viscosity from 2.6×10^{-3} to 15×10^{-3} Pa.s.

MATHEMATICAL MODELS AND PARAMETERS

Gas flow pressure drop and loading point

The experimental investigations of the pressure drop of Holpack was carried out [6, 13, 14] mostly in an air–water system. The following packings were tested (Table 1): Nos. 1÷4, 13, 15, 17 and 20. To estimate the influence of liquid phase viscosity some experiments were also carried out with irrigation by an aqueous solution of sugar [6, 13, 14].

Figure 3 depicts the typical dependence of the pressure drop for Holpack No. 4.

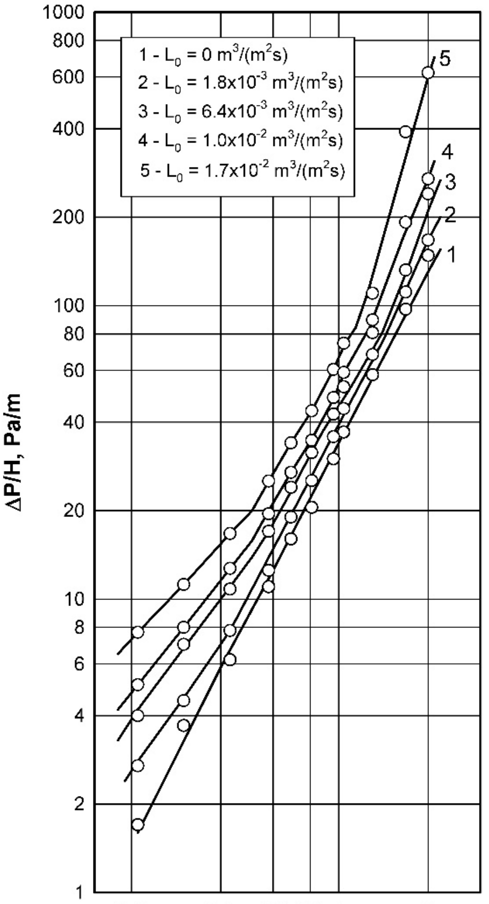


Fig. 3. Pressure drop of packing Holpack No. 4 (Table 1) depending on the gas velocity

Analogous dependencies are observed for the other investigated packings. The obtained experimental data are compared with the pressure drop of metal structured packings Montz B1-250, Mellapak 250 X, Mellapak 250 Y and Sulzer BX [15-19]. Closest to their dry packing pressure drop is the packing No. 20 (Table 1). The comparison of the wet packings Montz B1-250 and Mellapak 250 X [16-18] with packing No. 20 shows about two times lower pressure drop of Holpack at similar conditions. In the same works, the earlier models and equations for determination of the pressure drop of dry and irrigated Holpack packing, as well as for loading point gas velocity were also proposed. Subsequently, after a careful critical analysis on the base of many years' practical (incl. industrial) experience some imperfection of these dependences and, respectively, opportunities for substantial improvement were found. As a result, new more accurate models and equations for determination of gas pressure drop characteristics were developed [20].

It should be underlined that in the new equations the same experimental data are used as in the old ones. The principal differences evolve from the new structure of the equations, proposed striving to be closer to the real physical phenomena typical of the gas pressure drop in tubes and channels [20]. In this way, using the dimensional analysis, a more realistic estimation of the influence of the geometric dimensions (mainly the packing sheet free cross-section) can be made. For example, this parameter appears in the new structure only as a part/term of the dimensionless numbers, not as a separate one. Further, in the new derived equations the packings Nos. 1÷4 were excluded because of their "opposite" arrangement. As will be shown later, this arrangement has about 14% less effective specific area of the irrigated packing than the "crosswise" arrangement at equal conditions and didn't find practical application due to lower efficiency.

The new equations, presented below, were derived using dimensional analysis and least-square approach regression. Here the equation form reflects the flow pressure drop in tubes and channels. The *Euler* number (*Eu*) is defined as a ratio between the static pressure drop of the packing and the dynamic pressure (see Eq. 5). The main difference from the old equation is that the free cross-section of the packing sheet (ε_1) is not involved as a main dimensionless variable. After each equation the main statistic parameters as the mean arithmetic error (MAE) (absolute value) and the standard deviation (SD) are given.

- Pressure drop of dry Holpack packing (ΔP_0)

$$Eu=\left(0.0343+\frac{2.16}{\mathrm{Re}_G}\right)N_1\left(\frac{H}{d_h}\right)\left(\frac{h_1}{d_h}\right)^{2.47}Re_G^{0.112};$$

MAE = 7.88%; SD = 12.6% (2)

- Pressure drop of irrigated Holpack packing (ΔP)

$$\frac{\Delta P}{\Delta P_0}=0.884\,\mathrm{Re}_L^{0.17}\left(\frac{s_1}{d_h}\right)^{-0.25}\mathrm{Re}_G^{0.054}; \qquad (3)$$

MAE = 5.5%; SD = 8.6%

- Loading point gas velocity (w_{0G})

$$MFr_G = 1.97\left(\frac{s_1}{d_h}\right)^{-0.90} Fr_L^{-0.112}\ ; \tag{4}$$

MAE = 4.56%; SD = 7.67%,

where the dimensionless numbers are defined as:

$$Eu = \frac{2\Delta P_0 \varepsilon_1^2}{w_0^2 \rho_G} \quad \mathrm{Re}_G = \frac{w_0 d_h}{\nu_G \varepsilon_1} \quad \mathrm{Re}_L = \frac{L_0 d_h}{\varepsilon_1 \nu_L}$$
$$Fr_L = \frac{L_0^2}{g d_h \varepsilon_1^2};\ MFr_G = \sqrt{\frac{w_{0G}^2}{\varepsilon_1^2 d_h g}\left(\frac{\rho_G}{\rho_A}\right)} \tag{5}$$

Here the *Euler* number (*Eu*) reflects the ratio between the static pressure drop of the packing and the dynamic pressure. It should to be pointed out again that ε_1 is the packing sheet free cross-section and is not equal to the packing void fraction ε (see Eq. 1b).

Dynamic liquid hold-up

The liquid hold-up of the packing is a sum of static and dynamic hold-up. Because of the construction of Holpack packing its static hold-up can be neglected. The research of the dynamic hold-up of Holpack packing [14, 21] is carried out using packings with diverse characteristics (Table 1). The irrigation density is varied between 1.5×10^{-3} and 1.7×10^{-2} $m^3/(m^2s)$. The whole research is done without gas flow because it is known that up to the loading point, packing hold-up does not depend on the gas velocity. Liquid viscosity is changed within the limits from 1.0×10^{-3} to 1.3×10^{-2} Pa.s and the density – from 1000 to 1230 kg/m^3. The results are shown in Figure 4 as a dependence on the water irrigation density.

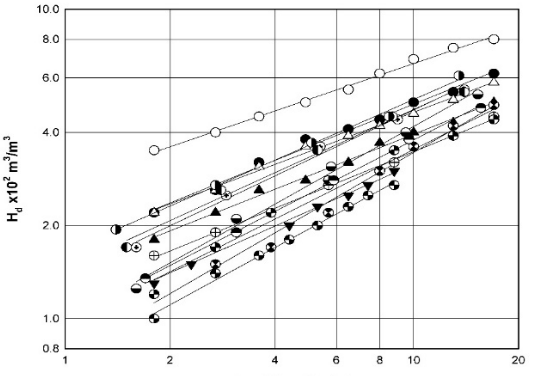


Fig. 4. Experimental data for the hold-up of Holpack packing (Table 1), depending on the irrigation density

For determination of the dynamic hold-up of Holpack packing (below the loading point) the following equation is derived [14, 21]:

$$H_d = 0.47 Ga_L^{-0.05} Fr_L^{0.22}\ , \tag{6}$$

where the numbers of *Galilei* and *Froude* are defined by the expressions:

$$Ga_L = \frac{g}{a^3 \nu_L^2};\quad Fr_L = \frac{L_0^2 a}{g}\ . \tag{7}$$

The deviation between the experimental data and Equation (6) is within ± 20%.

A careful consideration of Figure 4 shows very low values of the liquid hold-up of Holpack packing, which is due to its construction. It should be noted that this is a very good characteristic with a view to its industrial application, which makes the technological apparatuses with this packing quite flexible at variation of the operating regimes.

It can be said that liquid hold-up values for Holpack (Table 1) are approximately between 1 to 4 % for a very wide range of liquid rates. Compared to modern structured packing like Mellapak 2X, Flexipac 2Y HC, B1-250M and Mellapak 250 X, Holpack liquid hold-up values are lower or equal to the values of liquid hold-up for structured packings [16, 21]. In [21] the values of liquid hold-up have been determined for 3 different systems: air/water, air/sugar/water 5×10^{-3} Pa.s and air/sugar/water 12×10^{-3} Pa.s. In [16] liquid hold-up values are obtained for air /water and air/MEA 30 % wt systems.

Liquid distribution

The uniform radial liquid distribution is a crucial condition for the normal operation of packed columns. For this purpose, uniform initial liquid distributions at the top of the packing layer, as well as its maintenance along the column height must be provided.

For the initial distribution in the industrial columns normally multipoint distributing devices are used. Then the distribution uniformity in the upper zone of the packing depends on the design of the distributing device (mainly the distance between the jet points) and the redistribution (spread) ability of the packing. The latter is expressed by the liquid radial spreading coefficient D_r. This coefficient is usually experimentally determined by the method of Kabakov and Dilman [22]. This method is still in use both for random and structured packing to obtain information about spreading coefficient [16, 23].

Table 2. Geometric dimensions of the investigated Holpack packings for determination of their liquid spreading coefficient and its experimental values

No	Sym-bol	A mm	B mm	C mm	δ mm	s mm	s_1 mm	h_1 mm	h_2 mm	d_h mm	a m^2/m^3	D_r mm
1	○	22.2	30.7	6.4	0.8	5.0	4.0	3.0	10	6.5	125	1.0
2	●	22.2	30.7	6.4	0.8	5.0	4.0	3.0	20	6.5	70.0	1.0
3	◑	22.2	30.7	6.4	0.8	5.0	4.0	3.0	50	6.5	31.0	1.0
4	△	90.0	122	23.8	3.0	13.0	13.0	11.0	10	17.0	70.0	1.8
5	▲	90.0	122	23.8	3.0	13.0	13.0	11.0	20	17.0	47.4	1.8
6	⨹	90.0	122	23.8	3.0	13.0	13.0	11.0	50	17.0	23.8	1.5
7	▽	85.0	114	36.0	4.0	16.0	24.0	17.5	10	20.8	61.6	5.7
8	▼	85.0	114	36.0	4.0	16.0	24.0	17.5	20	20.8	45.2	5.7
9	⛛	85.0	114	36.0	4.0	16.0	24.0	17.5	50	20.8	25.1	3.5

The investigations for the spreading coefficient of Holpack packing are carried out at spreading a single jet [24]. The device used for this purpose is a cylindrical section with a diameter of 470 mm in which the liquid is fed axially at the top of the packing. The packing layer height is varied from 100 to 370 mm depending on its type. In all cases a "crosswise" arrangement of the packing is used.

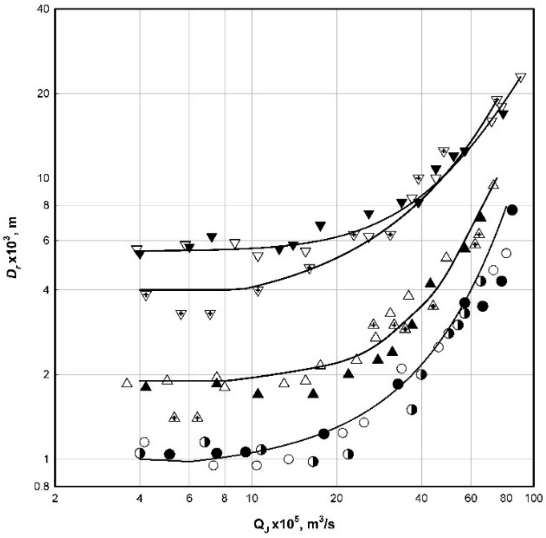


Fig. 5. Dependence of the distribution coefficient of different types of Holpack packing (Table 2) from the flow rate of a single jet.

The liquid, spread in the packing, is collected below the packing in concentrically situated cylinders, which also serves as a supporting grid. The value of D_r is determined by the above-mentioned methodology [22]. The obtained results are presented in Figure 5. The characteristics of the investigated packings and their symbols are given in Table 2.

Figure 5 shows that at a flow rate of the single jet of about 1.4×10^{-4} m^3/s, the coefficient D_r does not change, while raising the flow rate above this value leads to its increase. The experiments also show that at a distance between the packing sheets of 10 and 20 mm, the values of the radial spreading coefficient are close to one another. Data at a distance of 50 mm lie lower in the area of the smaller flow rates. At increasing the flow rate of the single jet, the values of the coefficient come closer. Considering the perceived methodology [22], the values of the radial spreading coefficient are determined only at the horizontal section of the dependency on Fig. 5.

Applying the dimensional analysis to the data for all investigated packings in the area, where the flow rate of the single jet does not affect the distribution, the following equation is obtained [24]:

$$\frac{D_r}{s_1} = 27\left(\frac{h_1}{s_1}\right)^{2.9}\left(\frac{h_1+h_2}{s_1}\right)^{-0.18}\left(\frac{\delta}{s_1}\right)^{2.2} \qquad (8)$$

The mean arithmetic error (MAE) of Equation (8) is 11 % and the confidence interval at 95 % statistical safety is 5.8 %. The maximal error does not exceed 27 %.

Because of the low values of D_r, Holpack packings Nos. 1÷3 are not suitable for a redistribution layer. To determine the radial spreading coefficients of the packings Nos. 4-9 only the following modified equation is proposed [24]:

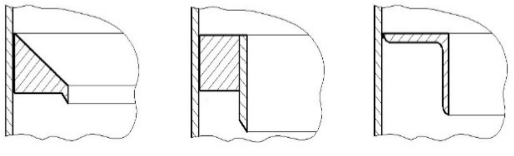
$$\frac{D_r}{s_1} = 0.133\left(\frac{h_1}{s_1}\right)^{-2.0}\left(\frac{h_1+h_2}{s_1}\right)^{-0.38} \qquad (9)$$

The mean arithmetical error of Eq. (9) is 8.9 % and the maximal one does not exceed 20 %. The confidence interval at 95 % statistical safety is 5.6 % and at 90 % statistical safety is 4.7 %.

In Table 2 are given the values of the distribution coefficient for the investigated 9 Holpack packings. The higher values for packings Nos. 4÷9 make them rather promising to be used as a redistribution layer above packings with low distribution ability. Additional warranty for this is provided by the higher admissible velocities for them. These values are comparable or a little higher than the corresponding value for Mellapak 250 X (between 3 and 4 mm, depending on the investigated liquid phase) [16]. The difference in specific surface between Holpack and Mellapak 250 X has to be noted. Higher values of the distribution coefficient D_r lead to lower requirements to the liquid distributors used in columns with Holpack packing. Conditions are created for using more simple design of distributing devices with a smaller number of distributing points per unit of cross-section of the apparatus. The higher spreading ability of this packing combined with the tendency of the liquid in such columns to spread towards the wall, lead to a strengthening of the wall effect [2, 14, 25, 26]. This causes a variation of the gas–liquid ratio along the apparatus cross section and particularly in the wall zone. The liquid there less actively participates in the mass transfer process than in the bulk of the column. Thus, the wall layer appears to be a bypass to a great extent, which significantly decreases the column effectiveness as a whole. Holpack packing construction itself creates conditions for increasing this effect. The sheets usually do not stick tightly to the column wall because of construction tolerance and because of tolerance related to the ellipticity of the column case. This leads to pouring more liquid on the wall from the peripheral elements of the sheet, than they take away and send back to the bulk of the packing. This way a bigger wall flow is formed.

To limit or eliminate the detrimental influence of the wall flow the so-called Wall Flow Deflecting Rings (WFDR) are proposed [25]. They are narrow (about 5 – 25 mm) rings with a profile suitable to deflect the wall flow (Fig. 6), which are situated at a distance of 100 – 300 mm from one another on the internal side of the column. Version (a) is better for pilot investigations at a column diameter up to 200 mm. For industrial apparatuses the exemplary variants (b) and (c) are more suitable because of the simpler implementation.

For determination of the influence of WFDR at Holpack packing, an experimental study is carried out with 4 packing types Nos. 5, 13, 19 and 20 from Table 1 in a column with a diameter of 190 mm [26] and deflecting rings with a width of 5 mm. As a model process/system the desorption of CO_2 from water in air flow is used. The amount of the liquid flowed in the wall zone, as well as the mass transfer in the liquid boundary layer in the wall zone and in the bulk of the packing at the end of the column is investigated. The influence of the distance between the deflecting rings along the apparatus height on these results is also examined [14].



(a) (b) (c)

Fig. 6. Sketch of wall flow deflecting rings (WFDR)

Figure 7 shows the influence of the irrigation density on the height of transfer unit (HTU), the wall zone and in the bulk of the packing. For this purpose, special liquid collecting cells for both zones were used. The obtained results [26] show that at density of irrigation from 2×10^{-3} to 1×10^{-2} $m^3/(m^2s)$, i.e., in the area important for the industrial practice, HTU in the wall zone is between 40 and 80 % bigger than HTU in the bulk of the packing. The data using WFDR are also shown. It can be seen that at a distance between them of 200 mm, HTU in the wall zone is practically equal to that in the bulk zone.

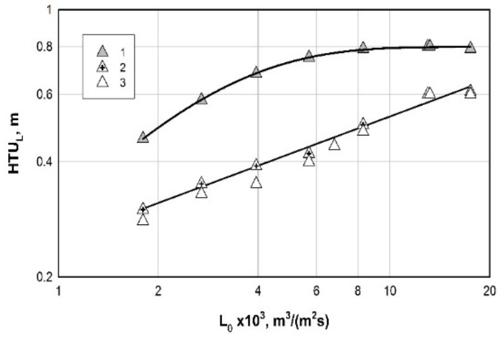


Fig. 7. Influence of the irrigation density on the height of a transfer unit for packing Holpack No. 2 (Table 2). 1 – at the wall zone without WFDR; 2 – at the wall zone with WFDR at a distance of 200 mm; 3 – in the bulk of the packing.

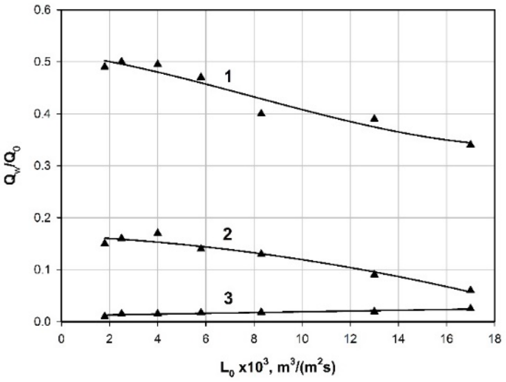


Fig. 8. Influence of the irrigation density on the distribution of the liquid to the wall of the apparatus at different distances between the WFDR. 1 – without rings; 2 and 3 – distance between the rings of 200 and 100 mm.

The results [26] of the study of the flowing of the liquid towards the column wall with and without

WFDR are shown on Fig. 8. Almost fully averting of this flowing is observed at a distance of 100 mm between the rings. The experience at the further application of WFDR shows that they successfully eliminate the wall flow in larger-scale, including industrial apparatuses. The width of the rings should be bigger than the width of the actual slot/gap between the end of the packing sheet and the wall of the apparatus. The rings used in the practice are within 10 and 25 mm wide.

Gas distribution

The uniform distribution of the gas velocity across the packed columns cross-section is an important condition for their normal operation. Non-uniformity conditions for local irregularity of the gas-liquid ratio are created, resulting in decreasing of the actual average concentration difference in the apparatus and thus in lowering of the effectiveness of the mass and heat transfer process.

One of the main sources for unequal gas distribution is its introduction in the apparatus. The equalizing action of the packing is caused by its resistance distributed on the cross-section of the column. It makes the flow to redistribute on the front but at the same time to move through the openings of the packing elements. Holpack packing is actually a system of consecutively situated grids of expanded metal sheet. Owing to the gradual flow from one grid to another at comparatively low values of the resistance coefficient, a fast uniform distribution of the velocity across the cross section is reached. The significant mixing of the gas phase in radial direction in volume between the sheets is essential in this process.

The study of Darakchiev [27] aims to determine the minimal packing height, at which a uniform gas distribution on the column cross section with sufficient accuracy for the practice can be assumed. The experiments are carried out with several types of random packings, plastic Pall rings 50 mm and ceramic saddles Intalox 35 mm among them. Four types of Holpack packings are investigated (packings Nos. 1, 3, 7 and 9 from Table 2), as well as packing No. 1 from Table 1 without distance between the sheets, for comparison. The diameter of the experimental column is 470 mm without irrigating liquid. The air flow velocity is measured with a thermo anemometer. The sensitive element of the device (the probe) is attached to a stand with a possibility for a movement along two perpendicular diameters of the column cross section. It is situated at a small distance from the upper end of the packing. Because of its high sensibility to turbulent pulsations and to increase the measurement accuracy, an averaging of the signal is done with analogue computing machine.

An estimation of the degree of non-uniformity of the velocity distribution on the cross section is performed with regard to the maximal flow velocity related to the average velocity on the cross section ($w_{\max}/w_0$). In this research the equalization of the velocity profile is accepted at a maldistribution degree of 1.25.

The expanded metal sheets of the investigated Holpack packings have a big free section (over 80 %). The experiments show that at initial maldistribution reaching 2 (200 %) (see Fig. 9), the number of the sheets needed to reach the wanted degree of maldistribution (equalization of the velocity profile) is 5–12 (Fig. 10). The hydraulic diameter of the openings d_h, as well as the distance between the sheets h_2, where the radial gas redistribution passes brings influence to bear on this. The determined heights for uniform distribution are: for packing No. 1 - 0.146 m; No. 3 - 0.268 m; No. 7 - 0.320 m and No. 9 - 0.355 m. The plastic Pall rings of 50 mm and ceramic saddles Intalox of 35 mm show equalization of the profile at a layer height of 0.8–1 m. The mean air velocity within the researched range from 1.1 to 2.5 m/s has no significant influence on the flow distribution. The research is also done at different initial maldistributions caused by different gas inlet devices in the column.

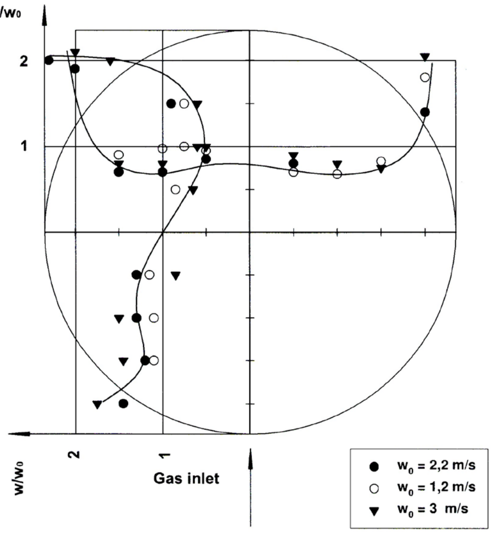


Fig. 9. Distribution of the ratio of local to mean gas velocity on the cross section of a column with a diameter of 470 mm on a distance of 100 mm below the packing grid by two mutually perpendicular directions.

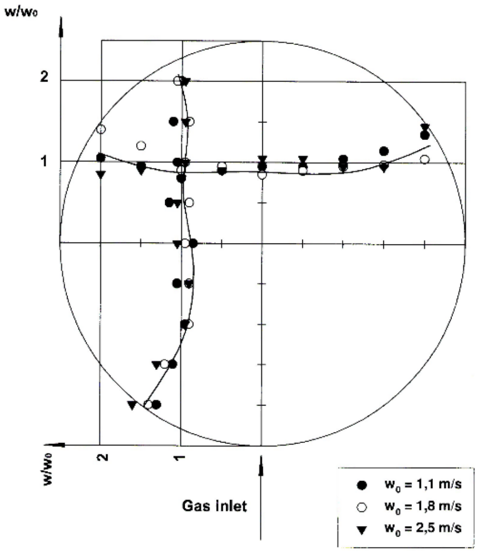


Fig. 10. Distribution of the ratio of local to mean gas velocity on the cross section of a column with a diameter of 470 mm for packing Holpack No. 21 (Table 1) with a height of 0.215 m.

In the presence of a counter-currently moving liquid up to the loading point (the area in which the heat and mass transfer packed apparatuses usually operate), the interaction between the phases can be neglected by definition and the picture would not significantly change. The flowing liquid will occupy a part of the cross section; it will reduce the void section of the packing and will increase the smoothing action of the packing layer. The gas distribution is also estimated by means of the maldistribution factor [28-30], using the same experimental data [30]:

$$M_f = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{w_i - w_0}{w_0}\right)^2} \qquad (10)$$

where: w_i is the local velocity of the gas in the i-th measuring cell, m/s and n is the number of measuring cells.

A very important index, which can be evaluated using this parameter, is the uniformity limit. It shows the minimal possible maldistribution for every packing type and results from its discrete structure. For packings with distance between the sheets of 10 and 50 mm, the uniformity limit is at maldistribution factor $M_f = 0.19$ and $M_f = 0.18$, at the lack of distance [29]. This shows that the distance between the packing sheets is very important for equalizing the gas velocity profile.

Effective surface area

Knowing the effective interphase area is a crucial moment in studying the mass- and heat transfer in packed columns. The research works for determination of the effective area of Holpack packing are carried out mainly by [2, 14, 31]. They are made by the method using a chemical reaction of pseudo-first order. As a model system the absorption of CO_2 from NaOH solution is used.

The obtained experimental data for the investigated packings (Table 1) are presented as a dependence between the specific effective interphase surface area and the density of irrigation (Fig. 11).

Processing the obtained experimental data for determination of the specific effective inter-phase area of Holpack packing the following equation is obtained [14, 31]:

$$\frac{a_e}{a} = C_1 E\ddot{o}^{0.28} Fr^{0.066},$$

$$\text{for } E\ddot{o} = \frac{\rho_L g}{\sigma a^2} \text{ and } Fr = \frac{L_0^2 a}{g} \qquad (11)$$

where C_1 = 0.95 for crossed sheet arrangement and C_1= 0.82– for opposite arrangement.

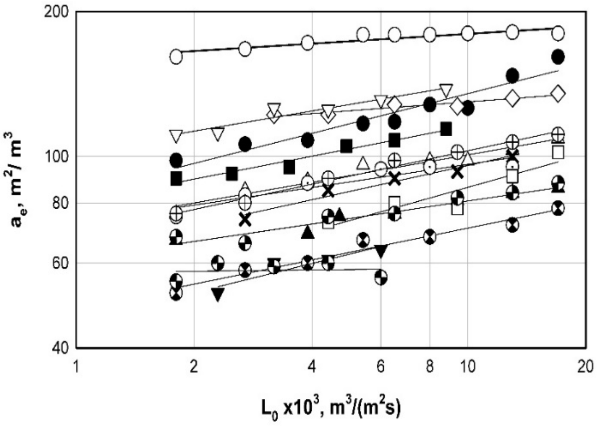


Fig. 11. Dependence of the effective specific surface area of Holpack packing (Table 1) on the irrigation density.

The comparison shows that 93 % of the experimental data have a maximum deviation of ±15 % from the values computed by Eq. (11) Because of the higher specific effective area at crossed sheet arrangement at equal geometric characteristics, this arrangement has been implemented into practice. The ratio between the effective and the specific geometric area for Holpack packing is of especial interest because of its design and principle of operation. The results [2] are shown on Fig. 12.

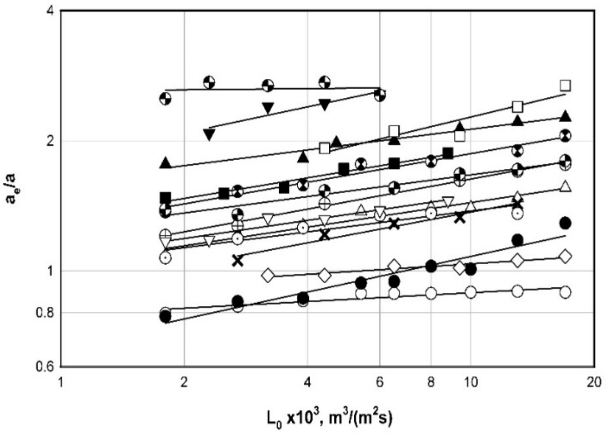


Fig. 12. Dependence of the ratio of the effective to the specific surface area of Holpack packing (Table 1) on the irrigation density.

There can be seen that for this packing, this ratio can reach 3, as the other values are between 1 and 3. This is due to the phase surface of the drops and jets in the empty spaces between the packing sheets. Such effect is also observed for random packings with an open structure and large free volume where the ratio between the effective and the geometric area does not exceed a value of 2 [32].

Axial mixing in the liquid phase

The axial mixing is a hydrodynamic phenomenon which decreases the driving force of the process and at definite conditions can significantly reduce the effectiveness of the packed column [5, 33]. The axial mixing is inevitable and at uniform radial distribution of the phases it reflects the possibly minimal small-scale maldistribution, which is due to the discrete structure of the packing. Particularly important is the influence of the axial mixing in the liquid phase at low irrigation densities, while in the gas phase the influence of the axial mixing is weak and for Holpack it is assumed to be insignificant [5, 34], mainly because of its design, which contributes for the equalization of gas velocities on the column cross-section. The influence of axial mixing is taken into account using the dispersion mathematical model with hydrodynamic parameter the dimensionless number of Bodenstein. In this number the axial mixing is reflected by axial mixing coefficient as an analogue of the axial turbulent diffusion.

The axial mixing in the liquid phase in columns with Holpack packing is studied [33, 34] at irrigation with water and without air flow by the method using an electrolyte tracer that is fed above the packing as a δ-impulse. Both flows – water and tracer are uniformly distributed over the column cross-section. To increase the accuracy, the disturbing influence of the conductometric cell is additionally accounted for by the method described in [35]. Five types of packing are investigated (Table 3) in a column with a diameter of 190 mm over a wide range of variation of the irrigation densities from 3.0×10^{-4} to 1.5×10^{-2} $m^3/(m^2s)$.

One peculiar feature of the axial mixing in the liquid phase is observed for Holpack packing that is due to the packing operating principle. Two regimes are identified [34] provisionally called “drop” and “jet” regimes, where the dependency of the axial mixing by the irrigation density differs significantly. For the “drop” regime is obtained the Equation:

$$Bo_L = 0.029(ah_1)^{0.43}\,\mathrm{Re}_L^{0.39}(aH)$$
$$\text{for } \mathrm{Re}_L < \mathrm{Re}_{LCr}, \tag{12}$$

and for the “jet” one:

$$Bo_L = 1.62x10^{-5}\,Ga_L^{0.81}(ah_1)^{0.31}\,\mathrm{Re}_L^{-0.83}(aH)$$
$$\text{for } \mathrm{Re}_L \geq \mathrm{Re}_{LCr}. \tag{13}$$

The mean arithmetic error of Equation (12) is 9.3 % and that of Equation (13) is 16.2 %. The transition between both regimes is determined by the critical value of the Reynolds number, defined by the equation:

$$\mathrm{Re}_{LCr} = 2.18x10^{-3}\,Ga_L^{0.66}(ah_1)^{-0.096} \tag{14}$$

Table 3. Geometric dimensions of Holpack packings, used for the research of the axial mixing in the liquid phase and for the first investigations at rectification.

No.	*A* *mm*	*B* *mm*	*C* *mm*	*δ* *mm*	*s* *mm*	*s$_1$* *mm*	*h$_1$* *mm*	*h$_2$* *mm*	*d$_h$* *mm*	*a* *m^2/m^3*	*ε$_1$* *%*
1	21.2	29.2	9.3	1.0	6.3	4.6	3.9	50	8.0	24.9	83.4
2	21.2	29.2	9.3	1.0	6.3	4.6	3.9	25	8.0	46.5	83.4
3	21.2	29.2	9.3	1.0	6.3	4.6	3.9	9.3	8.0	102	83.4
4	73.8	114	21.6	3.0	15.4	12.0	11.5	50	20.6	22.7	81.4
5	73.8	114	21.6	3.0	15.4	12.0	11.5	25.1	20.6	38.2	81.4

The criteria of Bodenstein, Reynolds and Galilei in Equations (12÷14) are defined as follows:

$$Bo_L = \frac{L_0 H}{\varepsilon_1 H_d D_{TL}}; \quad \mathrm{Re}_L = \frac{4L_0}{a\nu_L}; \quad Ga_L = \frac{g}{a^3 \nu_L^2}$$

where D_{TL} is the axial mixing coefficient in the liquid phase.

The physical explanation for the existence of these regimes follows by the operating principle of the packing. At low loads the liquid flows down by drops consecutively from sheet to sheet through the packing. On increasing the irrigation density, the small-scale radial uniformity of the flowing drops improves and this leads to a lowering of the axial mixing and respectively increases the apparatus effectiveness. On further increase of the load jets are forming that flow with different velocity and the axial mixing becomes higher again.

From Equations (12÷14) it can be seen that at “drop” regime the Bodenstein number increases with increasing the irrigation density while at the “jet” regime (above the critical value of Reynolds number) the dependency is opposite. Since on increasing the values of Bodenstein number, the influence of the axial mixing goes down, it follows that for Holpack packing there is an optimal operating range with maximal effectiveness around the point of the transition between both the regimes. The comparison between the corresponding equations [5] for determination of Bodenstein number for Holpack packing and for conventional ceramic random packings shows that at equal specific surface area in drop regime (below Re_{LCr}) the coefficient of axial mixing in the liquid phase for Holpack is up to 4 times smaller.

In the study [36] the axial mixing in the liquid and gas phases of metal Pall rings 25, metal Intalox saddles 25 and Mellapak 250Y was investigated. For the liquid phase a similar tracer method was applied, but using stepwise tracer injection instead of δ-impulse and two conductometric sensors located on certain distance in order to improve the experimental accuracy. Equations for Bodenstein number of each type of packing were worked out. The comparison with Holpack, e.g., No. 5 from Table 3 in the optimal operation zone ($\sim \mathrm{Re}_{LCr}$) shows that the coefficient of axial mixing for 1 m packing layer of Holpack packing is 10.8 times smaller than of Pall 25, 11.8 times than of Intalox 25 and 5.7 times than of Mellapak 250Y.

The above comparisons give a significant advantage to Holpack packing to carry out processes at the conditions of which the influence of the axial mixing in the liquid phase is high. In the jet regime (above Re_{LCr}) the axial mixing coefficient can be bigger than that of the random packings but then as a rule the influence itself of the axial mixing on the mass transfer effectiveness in packed columns decreases because of the increase of the height of transfer unit ($\mathrm{HTU_L}$) [33].

Mass transfer controlled by the gas boundary layer

The experiments for determination of mass transfer coefficients at a process controlled by the gas boundary layer are carried out in columns with diameters 190 and 470 mm [2, 37]. The process of absorption of ammonia with a concentration of 0.5÷1 % in pure water is used. Because of the high rate of the absorption process, the gas concentration at the end of the apparatus is quite low. To obtain the desired accuracy of the experimental research, the heights of the investigated packings are within the range of 0.5 ÷ 1 m. The smaller packing heights are related to packings with a small equivalent diameter and smaller distance between the sheets.

Figure 13 shows the dependency of the volumetric mass transfer coefficient for mass transfer controlled by the gas boundary layer on the gas velocity at irrigation densities of 3.3×10^{-3} $\mathrm{m^3/(m^2s)}$ (for packings Nos. 1, 5, 18 and 20) and only 8×10^{-3} $\mathrm{m^3/(m^2s)}$ is for packing No. 15 (Table 1). The experimental results are compared with these of the metal structured packing Mellapak 250 X with $a=205$ $\mathrm{m^2/m^3}$ [38]. The comparison is made with Holpack packing No. 20 at $w_0 = 1.5$ m/s and $L=3.9\times10^{-3}$ $\mathrm{m^3/(m^2s)}$. The coefficient of mass transfer controlled by the gas boundary layer is 2.2 times higher for Holpack packing at equal pressure drop. This coefficient is by 70 % higher for Holpack compared with Mellapak 250 Y at the same velocity and $L=1\times10^{-2}$ $\mathrm{m^3/(m^2s)}$. This shows its possibilities to be applied in absorption processes and direct heat transfer.

After processing all available data of the mass transfer coefficient at mass transfer controlled by the gas boundary layer for Holpack packing the following equation is obtained [37]:

$$Sh_G = 0.26\,\mathrm{Re}_G^{0.73}\, Sc_G^{0.33} \qquad (15)$$

where the criteria of Sherwood, Reynolds, and Schmidt are defined by the expressions:

$$Sh_G = \frac{k_G\, d_h}{D_G}; \quad \mathrm{Re}_G = \frac{w_0 d_h}{\nu_G}; \quad Sc_G = \frac{\nu_G}{D_G}$$

The comparison between the experimental data and the results from Equation (15), shows that 93 % of them have deviation less than 20 %.

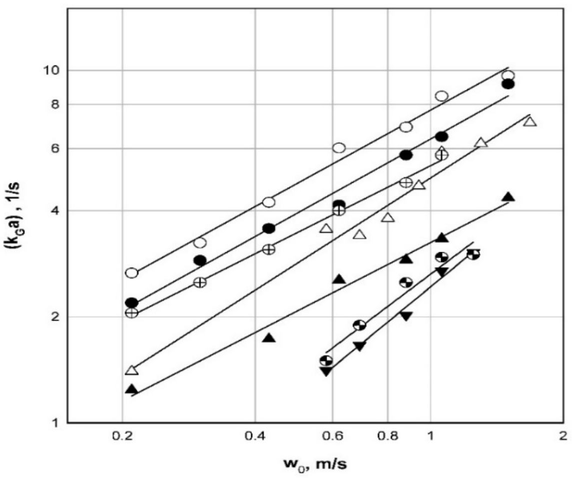


Fig. 13. Dependence of the overall mass transfer coefficient at mass transfer controlled by the gas boundary layer for Holpack packing (Table 1) at L_0 = 3.9×10^{-3} $m^3/(m^2s)$ (for packing No.15 – $L_0 = 8.10^{-3}$ $m^3/(m^2s)$).

Mass transfer controlled by the liquid boundary layer

- *Leaving out of account the axial mixing*

The determination of the mass transfer coefficient for a mass transfer controlled by the liquid boundary layer can be done by data for absorption (desorption) of weakly soluble gases. For Holpack packing research desorption of CO_2 from water solutions in an air flow is used. The experiments are carried out in two stands with diameters of the experimental columns of 190 and 470 mm. The height of the packing layer is within the range of 1 ÷ 2 m and the air velocity is 0.5 ÷ 1 m/s [2, 39].

The experimental data for the volumetric mass transfer coefficient for a mass transfer controlled by the liquid boundary layer as a function of the irrigation density of all of the investigated packings (Table 1) at 20° C and air velocity of 0.7 m/s are shown on Fig. 14. The obtained experimental results are compared with these of metal structured packings Mellapak 250 X and Mellapak 250 Y [40]. The comparison is made with packings Holpack No. 4 and No. 20 (Table 1) at w_0 = 1.4 m/s and L $=3.4\times10^{-3}$ $m^3/(m^2s)$. At a little lower pressure drop the mass transfer coefficients (k_La) are practically equal.

After processing all of the available data for Holpack packing to determine the volumetric mass transfer coefficient for mass transfer controlled by the liquid boundary layer the following equation is obtained [39]:

$$Sh_L = 1.13\text{x}10^{-3}\,\mathrm{Re}_L^{0.635}\,Ga_L^{0.366}\,Sc_L^{0.5}\left(s_1/h_1\right)^{4.0}\left(ah_1\right)^{0.1} \quad (16)$$

where the criteria of Sherwood, Reynolds, Schmidt and Galilei are defined by the expressions:

$$Sh_L = \frac{k_L h_1}{D_L};\quad \mathrm{Re}_L = \frac{4L_0}{a_e \nu_L};\quad Sc_L = \frac{\nu_L}{D_L};\quad Ga_L = \frac{g h_1^3}{\nu_L^2}$$

The comparison between the experimental data with Equation (16) shows that the deviations do not exceed ±20 %.

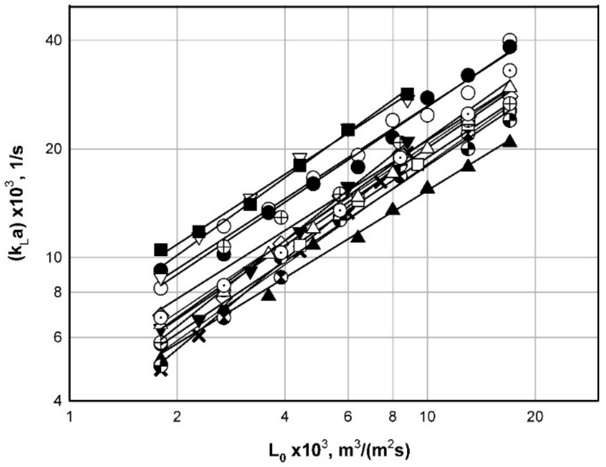


Fig. 14. Dependence of the overall mass transfer coefficient at mass transfer, controlled by the liquid boundary layer from the irrigation density for Holpack packing (Table 1) at w_o = 0.7 m/s.

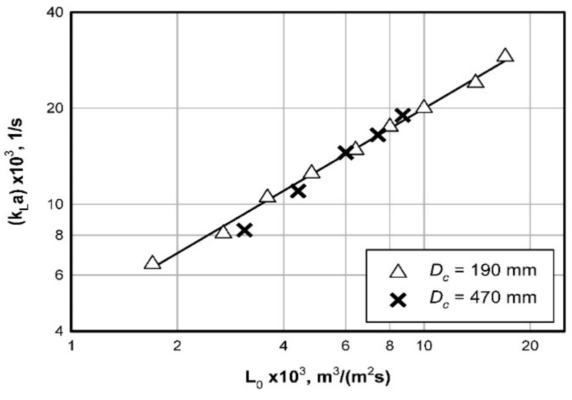


Fig. 15. Influence of the irrigation density on the overall mass transfer coefficient for two different diameters of the experimental column for packing No. 3 (Table 1).

On Figure 15 the experimental data [14] for the influence of the irrigation density on the overall mass transfer coefficient for packings No. 3 and No. 5 (Table 1) with equal geometric sizes, for two different diameters of the experimental column are presented. The good grouping of the points around only one line shows that at maintaining uniform irrigation, the column diameter does not affect the effectiveness of columns with Holpack packing. It should be noted that at processing the experimental data, the influence of the axial mixing for the conditions of the experiment is not considered and because of that it is implied in Eq. (16). The equation itself can be used only in the plug flow model within the range of its accuracy and at conditions similar or in reasonable deviations from these, at which it is derived in terms of the axial mixing. How to weigh up this is shown further down.

- *Considering the axial mixing*

The mass transfer coefficients in the liquid boundary layer suitable for using in the dispersion model should not include the influence of the axial mixing because it is taken into account in the model through the hydrodynamic parameter – Bodenstein number. The values of such mass transfer coefficients can be determined by experimental data at a process, controlled by the liquid boundary layer and consequent elimination of the axial mixing influence for the specific experimental conditions. Essentially this represents identification of the mass transfer coefficient in the dispersion model k_L^0 at degree of separation obtained from the plug flow model with mass transfer coefficient k_L at the same packing height and irrigation density. For this purpose, a method and a procedure are developed that are firstly applied for different types of random packings [33, 35]. Similarly, are processed all of the experimental data for the mass transfer coefficient for a process controlled by the liquid boundary layer for the Holpack packings from Table 1, used for working out Equation (16). The Bodenstein numbers are determined by Equations (12-14). The obtained results for the mass transfer coefficients, satisfying the dispersion model are generalized in the following equation [4, 5, 33]:

$$Sh_L^0 = 4.88\text{x}10^{-3}\,\mathrm{Re}_L^{0.49}\,Ga_L^{0.40}Sc_L^{0.5}\left(ah_1\right)^{-0.074} \quad (17)$$

where the Sherwood number is $Sh_L^0 = \dfrac{k_L^0\,h_1}{D_L}$, and the other criteria are defined as in Eq. (16). The mean arithmetic error of Eq. (17) is 11 %.

It is interesting to note that as a result of taking into account the axial mixing the exponent of Reynolds number in Equation (17) is considerably (with 25 %) smaller than that in Equation (16), e.g., the role of the most important hydrodynamic factor – the irrigation density, declines. This proceeds from the fact that the influence of the irrigation density is partly accounted for in the axial mixing. The simplex $\left(s_1/h_1\right)$ loses its significance in Eq. (17). This simplex characterizes the angle of the inclination of the expanded metal sheet lamellae and it is related to the direct falling of the liquid through the packing sheet. The mixing caused by this outstripping forms a part of the axial mixing and is taken into account by the dispersion model. However, the influence of s_1 remains with its participation in the effective specific surface area – Eq. (11) and the specific area – Eq. (1).

The importance of the mass transfer coefficient determination taking into account the axial mixing is shown in the study [41] as well. For this purpose, an alternative approach is proposed, the so called "profile method". This consists in the identification of the mass transfer coefficient on the base of the best fitting from concentration experimental data using the dispersion model and Bodenstein number equations. Experimental data from distillation in pilot plant with Mellapak 250 Y and Intalox 25 saddles were processed. It is highlighted that the dispersion model reproduces the concentration profiles better than the plug flow model.

- *Influence of the axial mixing*

To illustrate the influence of the axial mixing in the liquid phase for Holpack packing and the adequacy of its accounting for by the dispersion model and the plug flow model a comparison of the mass transfer coefficients satisfying the relevant models is made. The results are obtained with a numerical experiment and are presented on Fig. 16 in percent relative deviation between the coefficients as a function of the irrigation density [4]. The accomplished calculations show that from the packing geometric characteristics, the specific surface area has the most significant influence and because of that it is given as a parameter on the figure. The range from 20 to 100 m^2/m^3 is covered, which corresponds to the packings used in practice. The investigated interval of irrigation densities is 2×10^{-4} – 6×10^{-2} m^3/(m^{2}s), which is the whole range interesting for the practice. The packing height is assumed to be 1 m. The influence of other geometric dimensions is below 5 % and, in this case, average values are assumed (h_1=9 mm, s_1=11 mm). The liquid properties are accepted as for water at temperature of 20^0 C and for the coefficient of molecular diffusion – the values for CO_2 in water, e.g., at the conditions for experimental determination of the mass transfer coefficients. At the same conditions, both models have analytical solutions which are used at processing of the results. For all curves presented on Fig. 16 the mass transfer coefficients k_L^0 which satisfy the dispersion model are determined by Eq. (17) and the Bodenstein number needed to obtain the model solution – by

Eqs. (12 – 14).

For the curves of family A (Fig. 16) the mass transfer coefficients in the plug flow model k_L are identified by the analytical solution of the model at a degree of separation equal to that, determined by the dispersion model [4]. In this sense the curves show the effect of the axial mixing. Two branches are distinguished, related to the “drop” and “jet” regime, respectively. There can be observed a clearly pronounced minimum of the axial mixing effect (around 17÷19 %), where obviously is the optimal operating area of Holpack packing. From the curve’s family A it can be also seen (as was mentioned above) that at high irrigation densities in the “jet” regime the influence of the axial mixing on the efficiency remains relatively low although the axial mixing coefficient, determined by Eq. (13), strongly increases. The plug flow mass transfer coefficients for the curve’s family B are determined by Eq. (16). In this sense the curves show what effect of the axial mixing Eq. (16) expresses, applied, respectively, to the plug flow model.

From the comparison between the two curve families it can be seen that at low and high irrigation densities both models approximately equally express the influence of the axial mixing, while in a wide range of medium irrigation densities, important for the industrial practice, the difference is substantial. In this range the plug flow model can show significant deviations for the predicted effectiveness and, respectively, for the height of the packing layer. The good side in this case is that the plug flow model gives a raised value of the height, which is an additional safety oversizing.

The presented axial mixing effect explains the variable success when using the plug flow model especially at modeling the process of rectification with Holpack packing. That is why it is recommendable in all cases the dispersion model to be used with the corresponding equations for determination of its parameters. From the course of curves A on Fig. 16 the presence of optimal liquid load area for ensuring maximal effectiveness for a given packing and process conditions is obvious. This optimal area depends on the process conditions, as well as mostly on the characteristic sizes of the packing, which gives a possibility and guidelines for its improvement.

TECHNOLOGICAL RESEARCH AND INDUSTRIAL APPLICATION

- *For performing absorption and desorption*

The first studied process with Holpack packing is deaeration in experimental deaeration column. This is a process where oxygen is separated from water designed for feeding of steam boilers.

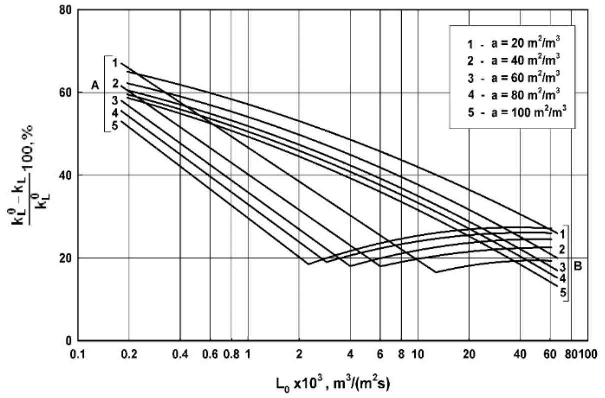


Fig. 16. Influence of the axial mixing in the liquid phase.

The water liable to deaeration is fed uniformly to a column with a diameter of 200 mm and packing No. 20 (Table 1) and steam is moving counter-currently. This packing structure enables quite big irrigation densities and steam velocities to be reached at uniform distribution of the phases on the cross-section of the apparatus and high mass transfer coefficient. The aim of the research carried out in the experimental deaeration column is to check the packing potentialities regarding the liquid and vapor load and applicability of the computing methodology.

For the dimensioning of deaerators, the plug-flow model is applied using the equations of mass balance and mass transfer, controlled by the liquid boundary layer [42]:

$$G = L_0\left(c_{in} - c_{out}\right) \tag{18}$$

$$G = k_L a_e H \Delta c_{av} \tag{19}$$

The mass transfer coefficient in Eq. (19) is estimated by the dimensionless Eq. (16) and its specific surface area – by Eq. (11). Because of the practically linear equilibrium concentration of the oxygen in a wide operation range the driving force is a mean logarithmic value of the difference of the incoming, respectively outgoing and the equilibrium concentrations of the oxygen in the apparatus, by the equation:

$$\Delta c_{av} = \frac{\left(c_{in} - c_{in}^{*}\right) - \left(c_{out} - c_{out}^{*}\right)}{\ln\left(\dfrac{c_{in} - c_{in}^{*}}{c_{out} - c_{out}^{*}}\right)} \tag{20}$$

The investigated deaerators [42] operated at atmospheric pressure (0.12 MPa), at vacuum (0.03 MPa) and under pressure (0.7 MPa). The irrigation density at the apparatus with atmospheric and increased pressure is 120 $m^3/(m^2h)$, and at vacuum - 110 $m^3/(m^2h)$.

The calculation shows a packing height for the experimental apparatus of 770 mm for atmospheric pressure, 1200 mm for vacuum and 1220 mm for increased pressure. On the walls of the pilot apparatuses deflecting rings are mounted at a distance of 200 mm from one another [42]. At initial (input) concentration of the oxygen in the water of 9.3 mg/kg, the end (outgoing) concentration decreases about 1500 times. It is considered that mounting of deflecting rings leads to a decline of the end concentration of oxygen in the deaerated water from 0.040 to 0.006 mg/kg.

The experiments show that the mass transfer coefficients in these apparatuses coincide with these at model research. Here is interesting to note that at the research conditions (mainly irrigation density around 3.3×10^{-2} $m^3/(m^2s)$ and specific packing surface area around 40 m^2/m^3), the plug flow model, by which the aerator is designed – Equations (19, 20) with mass transfer coefficients, determined by Equation (16), gives practically the same results as the dispersion model (Fig. 16).

The results obtained for deaerators with packing [42] are compared with the results for deaerators with standard perforated plates. The comparison shows that deaerators with Holpack packing have about 4 times smaller volume. The consumption of the ventilated stream is also several times reduced and is only 0.5 kg/t water. Reduced is the specific metal content as well. The oxygen concentration in the water at the end of the deaerators is according to the standard.

The research works carried out confirm the proposed computing methodology. They served for the development of industrial apparatuses with the following productivity: atmospheric and vacuum deaerators – from 2.5 to 25 m^3/h; atmospheric deaerators – from 50 to 250 m^3/h and deaerators under pressure of 0.7 MPa - from 100 to 350 m^3/h. These apparatuses operate successfully in many power plants.

One of the stages for processing of water for drinking and manufacturing purposes is the decarbonization– the separation of carbon dioxide. It is particularly often used in plants for water treatment for steam boilers. Usually the concentration of CO_2 in the water processed to decarbonization varies from 10 to 100 g/m^3, but in a number of waters with high carbon hardness, after H-cationization it can reach 500 g/m^3. The separation of CO_2 from water is performed in degassers, called in this case decarbonizers.

The most commonly occurring apparatuses of this type are packed columns. It was earlier established that the cheapest in terms of energy are degassers to be filled with Intalox saddles 38 mm. According to this important area of application experiments are carried out in decarbonization columns with Holpack packing No. 19 (Table 1). For determination of the dimensions of the experimental column the Eqs. (19), (20), (16) and (11) are used, since the mass transfer process is controlled by the liquid boundary layer. The aim is to determine the maximum load of the apparatus at a given output CO_2 concentration. The experimental column with capacity of 40 m^3/h is with diameter of 468 mm and packing height of 3400 mm. Wall Flow Deflecting Rings (WFDR) [25, 26] are mounted along the column walls with width of 12 mm and distance between them – 200 mm. The apparatus is mounted after the H-cationite filters of an industrial plant for steam boilers feeding water treatment.

A good conformity between the obtained mass transfer coefficients and those from the model research is established. The comparison of the results [43] with data from other used apparatuses shows the advantage of the degasser with Holpack packing because of the higher allowable loads and regarding the degree of CO_2 separation at given energy expenses. For all experiments at initial concentration of CO_2 40 g/m^3, the output one is within the range of $1.2 \div 1.8$ g/m^3.

The proposed equations for the Holpack packing characteristics are used for creation of many heat and mass transfer apparatuses. A semi-industrial monoethanolamine absorber with Holpack packing is designed and investigated, with a diameter of 500 mm and packed layer height of 5 m for purification of the technological gas used for methanol synthesis from hydrogen sulfide and CO_2 [44]. The experiments have shown that reloading of the existing absorbers from bubble-cap trays to Holpack packing leads to 5-times intensification of the process at 8-times reduction of the pressure drop. The comparative studies of monoethanolamine absorbers with three types of packings - structured Sulzer BX 500, Mellapak 500 Y and random Pall rings 16×16 mm published recently have shown advantages of the absorber equipped with Sulzer BX500 packing [45].

Application of Holpack in recent years is presented in new type of installation for SO_2 removal from flue gas, producing high-quality gypsum [46].

Also, an apparatus with the same packing for gas processing of the sodium-regeneration boiler at the production of sulfate cellulose is investigated. The aim is purification from dust, sulfur dioxide, other sulfuric compounds and heat utilization [47]. The apparatus has shown very good operation at these heavy technological conditions.

As a result of the research carried out it is established that in all cases the volumetric mass transfer coefficient of the industrial apparatuses coincides well with the coefficient estimated by the equations derived from the pilot research. The deviation, which does not exceed 20 %, is connected with the mass transfer below and above the packing in the industrial apparatuses. The loadings related to a unit packing volume, in industrial columns are bigger than in the apparatuses used before. Moreover, the degree of absorption (desorption) is equal or in most cases higher.

- *For performing distillation and rectification processes*

For the first time Holpack packing (Table 3) is studied for a rectification process by Semkov [33]. The investigations are carried out with a model system tetrachloromethane – chlorophorm at a regime of full reflux return and with four packing configurations. The experiments are performed in a column with a diameter of 0.207 m and packing height – 3 m. The column is mounted above a bottom part, in which electric heaters with total power of 54 kW are built-in, as this power can be gradually switched at intervals of 4.5 kW. The mass transfer and hydrodynamic results show that Holpack packing is suitable for rectification processes. The similar model system (Tetrachloromethane-Toluene) was investigated experimentally and semi-empirical model was proposed recently, but for sieve trays [48].

Later, the same packings (Table 3) are studied with an ethanol – water system [49]. The investigations are carried out at atmospheric pressure with five packing configurations, in a wide range of concentrations and phase velocities. It is established that the effectiveness strongly depends on the experimental operating concentrations. Because of that, further research is done at medium and high concentrations – just like those in the industrial columns for ethanol production.

The investigations at higher concentrations are carried out with two types of Holpack packing – No. 25 with small openings (d_h = 6.5 mm) and No. 26 with bigger openings (d_h = 25.6 mm (Table 1) [50, 51]. The results are presented as HTU and Height Equivalent to a Theoretical Plate (HETP). The packing with the bigger openings has shown better results.

At the investigations of the packing with the smaller openings (No. 25 from Table 1) experiments with variable reflux ratio are also carried out [52]. It is established that at reducing the liquid-vapor ratio, the effectiveness deteriorates. The effectiveness at a reflux ratio of 3.5, at which the real industrial plants for production of ethyl alcohol at atmospheric pressure operate, is also determined. The value of HTU is 0.42 in this case.

As a result of this research the developed unified mathematical model for dimensioning of packed columns for mass- and heat transfer processes [5] is verified. It takes into account effects of different origin, which occur as in absorption, as well as in rectification and direct heat transfer. Especially in rectification, particular attention has been paid on the turbulization of the inter-phase surface – the Marangoni effect [53], which affects the mass transfer coefficient in the liquid boundary layer. The axial mixing in the liquid phase is taken into account through the one-parameter dispersion model using Eqs. (12-14) for determination of the Bodenstein number and Eq. (17) – for the mass transfer coefficient in the liquid boundary layer. The axial mixing in the gas (vapor) phase is assumed to be insignificant because of the packing structure itself. The influence of the axial mixing in the liquid phase is studied on experimental data from a rectification of ethanol – water system. It is shown that in the range of the irrigation densities that are typical for this process this influence is essential and has to be taken into account by all means.

The proposed approach for calculating columns with Holpack packing [5] is successfully used in the realization of a large number of industrial projects [54]. On this basis 9 industrial plants for production of ethyl alcohol have been constructed, comprising 35 distillation and rectification columns with this packing (Fig. 17). The installations have productivity from 1,000 to 20,000 l/24 h. The columns are mainly supplied with packings No. 26 and No. 25 (Table 1).

The Holpack packing is successfully implemented in industrial plants for purification of waste waters from butyl acetate and butanol in antibiotics production [55]. This is accomplished in a stripping installation, which consists of two columns – a hollow and a packed column. In the plant for purification from butyl acetate, the column is with diameter of 800 mm and packing height of 2000 mm while in that for purification from butanol the diameter is 1200 mm and the height is 4000 mm.

The initial concentrations of butyl acetate in the waste waters in the plant for purification of butyl acetate are within 5.49 and 19.6 g/l, the steam consumption is from 0.055 to 0.200 kg/kg purified water, and the degree of purification is from 99.1 to 100 %. For the butanol plant the initial butanol concentration varies from 12.6 to 14.0 g/l, the steam consumption is 0.18 kg/kg purified water and the degree of purification is 99.9 %.

Fig. 17. Photograph of a rectification plant for ethanol production with productivity of 20000 litres/24h consisting of five columns with Holpack packing

Another realized application of Holpack packing is again in a stripping column, this time for purification of waste waters from chloroform [56]. The column is with diameter of 400 mm and packing height of 6400 mm. The amount of the treated water is within 1.8 and 2.2 m^3/h and the amount of steam is from 160 to 177 kg/h. The initial chloroform concentration in the waste waters is 7 g/l and the final (output) one varies from 0.044 to 0.164 mg/l. The degree of purification is in the range of 99.994 – 99.999 %. For both of the above-mentioned cases packing No. 24 (Table 1) is used.

Holpack packing is also used in the ethereal oil industry. The experiments have established that in cohobating columns for treatment of secondary distillation waters from essential oil production, the packing shows very good properties. As contact elements in the column packing No. 20 (Table 1) is used. The comparison with columns with other types of packing, including some modern random packings, shows that columns with Holpack packing have the highest effectiveness [57].

- *For performing direct contact heat transfer*

Increasing the economy of boilers, furnaces, dryers and other heat facilities depends on the reduction of the waste heat of the exhaust gases, which in the heat balance can be more than 10 %. To reduce the temperature of the outgoing gases various surface-type heat exchangers are commonly used. These facilities are metal-consuming, their sizes and expenditures are significant and they cause additional high resistance on the way of the gas. Another option is the direct phase contact heat exchange. The apparatuses operating on this principle have simple construction, compactness, low metal capacity and comparatively high heat transfer intensity due to the direct contact between the fluids. Using the contact heat exchangers (economizers) for utilization of the flue gases heat enables not only reducing the price of the utilizer but also assuring deeper gas cooling below the gas original dew point temperature, which is 58 - 61 ºC for the products of natural gas combustion. Besides, not only the sensible heat of the flue gases but also the latent heat of condensation of a part of water vapor content is recovered [58–62].

Direct contact gas cooling is accomplished mainly in a counter-current flow by water or another liquid. This liquid is used for heating of water or air for technological purposes. The most prevalent are the contact economizers with packing given that they provide a process possibly closest to a complete counter-current flow. The main part of the contact economizers is the contact camera, i.e., the part of the apparatus where the packing is placed and where the heat- and mass transfer process is going on most actively. There, a developed contact surface for the cooled gases and the liquid and also high intensity of the process per unit volume at possibly lower pressure drop have to be provided.

The available data for determination of the heat transfer coefficient are obtained for specific cases, and are related to processes in rather narrow borders. For this reason, it is advisable to seek other ways of determining it. One simplification of the task comes from the fact that the direct simultaneous heat- and mass transfer in a system water – gas (air) is connected with condensation of water vapors whereupon the process is controlled practically entirely by the gas boundary layer. To determine the heat transfer coefficient, the Lewis and Chilton-Colburn analogy between heat and mass transfer [3, 63, 64] can be used as is proven in [65].

Thus, analogically to equation (10) the following equation for the coefficient of heat transfer in the gas boundary layer can be written:

$$Nu_G = 0.26\,\mathrm{Re}_G^{0.73}\,\mathrm{Pr}_G^{0.33} \tag{21}$$

where the Nusselt and Prandtl numbers are defined by the expressions:

$$Nu_G = \frac{h_G d_h}{\lambda_G};\quad \mathrm{Pr}_G = \frac{\nu_G}{\alpha_G} = \frac{c_{pG}\mu_G}{\lambda_G}\ .$$

With its characteristics Holpack packing meets very well the requirements for performing heat- and mass transfer processes in contact economizers. It has a large interphase surface created in the first place by the surface of the drops and jets flowing from sheet to sheet, whereupon the liquid film is frequently broken and a renewal of the interphase surface is accomplished at a significant free volume.

For the determination of the packing height the plug-flow model consisting of the simultaneous heat- and mass transfer balance equations and the corresponding parameter expressions (11, 15, 21) is used [61, 65-67].

The experiments for verification of the model are carried out on a pilot plant with a contact economizer with packing Holpack No. 22 (Table 1) with a diameter of 470 mm and a height of a 1200 mm [68]. Flue gases are fed, obtained by the combustion of natural gas in a steam boiler with a capacity of 1.5 t/h steam. The gas velocity is varied within the range of $w_0 = 1.3 \div 3.4$ *m/s*, the irrigation density $1.2\times10^{-2} \div 2.8\times10^{-2}$ $m^3/(m^2s)$ and the initial moisture content of the gases 0.12 ÷ 0.41 kg/kg dry gas. The higher values are achieved by adding complementary steam to the flue gases. The obtained data are processed with software based on the proposed model.

In most of the cases the hot gases are obtained at the combustion of natural gas (NG). One interesting research of the possibility for using of the contact economizers with Holpack packing is presented in publication [66]. There, the flue gases are produced by the combustion of high-quality coal with low sulfur content.

In all cases considered so far, water is used as a liquid – heat transfer fluid. The maximal temperature, up to which theoretically the fluid can be heated, is the adiabatic saturation temperature of the gas. In a water - air/flue gas system this temperature coincides with the wet bulb temperature and the dew point temperature. For flue gases from NG burning at 1.1÷1.2 air excess it is about 60 ^{0}C. Technologies are developed [69] where the water can be heated to higher temperatures using high-temperature heat transfer fluid, for example oil.

- *Other processes suitable for Holpack packing application*

With its low pressure drop, high mass transfer coefficients and large interphase area, the Holpack packing is suitable for all kinds of absorption processes convenient for packed columns. Particularly appropriate for its implementation are those types of processes where the liquid – gas ratio is low. It is usually determined by the requirements of the mass and heat balances. In this case the column operates at low irrigation densities. At operating with Holpack packing, the effective area depends on the irrigation density weaker than at the random packings widely used in the industry. Such processes are almost all of the processes for purification of industrial flue gases that contain a small amount of absorbable component. One additional, quite important characteristic of the packing at such processes is its very good liquid distribution on the column cross-section.

The continuous change in the direction of the gas phase passing through the Holpack packing makes it appropriate for separation of the liquid phase from the gas flow. Devices made of expanded metal sheet are successfully used for reducing the carrying away of drops in a number of apparatuses. Practically, the total wetting of the packing, combined with the continuous change of the gas phase and the inertia forces arising from this change make the Holpack packing a particularly promising dust-catcher. Besides, its low pressure drop may be crucial for its application in this field. The packing's big free section and the lack of stagnation zones in it, make Holpack packing very convenient for operation with very dirty liquids and gases. This is particularly suitable in the cases where the solid phase does not tend to stick to the walls.

The Holpack packing can find prevalence in the direct cooling of water with air flow. Usually, the adiabatic water cooling in cooling towers is led at comparatively low irrigation densities where the Holpack packing is particularly suitable.

In this regard, cooling towers with this packing are constructed and implemented for cooling of the water from the condensers of the rectification columns of ethanol production plants. The towers are with a capacity of 12 and 40 m^3/h and packing height of 1500 and 1800 mm (Holpack No. 23, Table 1). The cross-sections of the towers are 2.25 and 3 m^2. The long observations and investigations show very good results for possibly the deepest cooling.

PACKING IMPROVEMENT AND INTENSIFICATION OF THE PROCESSES

The detailed research of Holpack packing, regarding its hydrodynamic and mass transfer characteristics, shows very good results. The developed methods for estimation and semi-industrial verification confirm the expected results. The designed and implemented into practice industrial apparatuses operate successfully in different areas of the chemical and food industry, the power sector and environment protection.

The Holpack packing is created on the basis of an existing configuration of expanded metal sheets. This is a standard machinery article, designed for other purposes. Nevertheless, the results show that it is close enough to the sheet shape, which can lead to still better results. Obviously, the principle of operation is felicitous and the same tendency should be followed to perfect this contact heat- and mass transfer device.

In order to improve the operation parameters of the packing, a detailed preliminary analysis of the factors that determine its characteristics should be done.

The investigation of the pressure drop of Holpack packing showed very low values of this parameter. This is due to its structure and the fact that its main elements are metal sheets with big free void. Our striving for reducing the metal capacity by decreasing the sheet thickness to 0.6 or 0.7 mm will lead to an increase in this section. Moreover, the distance between the sheets, which is usually in the range of 10 – 50 mm, is free and helps for the radial gas spreading and equalization of the velocity profile. Holpack packing provides a very good liquid spreading on the column cross-section. The investigations show that this strongly depends on its geometric characteristics – Eqs. (9) and (10). The packings with bigger geometric dimensions have higher spreading coefficients at smaller distances between the sheets (Fig. 5), which strongly depends on the geometrical dimensions and particularly on the h_1/s_1 ratio. This gives big possibilities for choosing the appropriate sheet dimensions, especially in accordance with their influence on the mass transfer characteristics.

The opportunities to improve Holpack packing and to intensify the processes in comparison with the current level can be easily identified, for instance, by the integral equation of the mass transfer (19). The quantities, which can be influenced at a given height, are mass transfer coefficients, effective surface area and mean integral driving force. To provide the maximal driving force and generally for the applicability of the mathematical models (plug-flow or dispersion model) it is necessary to create close to the ideal conditions, i.e. formation of uniform gas and liquid distribution on the cross-section of the apparatus and a regime of contact close to ideal counter-current flow. Then, for the plug-flow model the mean integral driving force is determined as a mean logarithmic concentration difference – Equation (20) and for the dispersion model it is obtained as an integral solution by taking into account the reducing influence of the axial mixing.

It can be seen from the research presented above that Holpack packing with its structure and principle of operation offers very good conditions for radial distribution of the phases. The gas quickly equalizes its velocity profile and the liquid, which is promptly spread, eliminates the risk of bypass flows. On the other hand, the deteriorative effect of the wall flow is avoided using wall flow deflecting rings, From Figures 7 and 8 it can be seen that conditions for uniformity of the flows are created. Hence, the construction of the packing forms conditions for assuring of maximal concentration difference. The other factor, which negatively affects the process driving force, as was pointed out, is the axial mixing in the liquid phase. It is inevitable, it is due to the discreet structure of the packing and the local phase contact surface and reflects the minimum possible non-uniformity of the distribution for a given geometric configuration and hydrodynamics of the liquid phase. Fortunately for Holpack packing, as was shown above, there is an optimal area of operation, which minimizes the detrimental effect of the axial mixing (see Fig. 16). As this area depends on the geometric configuration of the packing too, there is a possibility, using Equations (12-14) and (17), to foresee a packing with dimensions that assure the optimal operation at the conditions of a given process.

The other quantities which can used to make an impact on the intensification of the processes in Holpack packing are the mass transfer coefficients and the effective surface area. This is thoroughly related to observing the requirements of theory of tearing and renewing the mass transfer surface [3, 7-9].

In any case, apparently it comes into question to find an optimal combination of the values of s_1, h_1 and h_2, with a purpose of providing maximal effectiveness at given process conditions. These parameters influence through the specific packing surface – Equations (1); effective specific surface – Eq. (11); mass transfer coefficients – Eqs. (16, 17) and axial mixing coefficients – Eqs. (12 ÷ 14).

For instance, Figure 18 shows the influence of the distance between the packing sheets on the main hydrodynamic and mass transfer characteristics.

The detailed analysis, as well as the results from the practical application of Holpack packing show that the additional research for intensification of the packing has to be focused on a tentative distance between the sheets of about 20 mm. It probably creates the best harmony between the effective area of the packing sheets and that of the drops and jets in the empty space between them. This can be seen on Figure 19, where the number of the expanded metal sheets is given in dependence of the distance between the sheets h_2 at different hydrodynamic diameters of the openings. The work on optimization of the dimensions of the expanded metal sheets is eased by the die created and used for production of Holpack packing, assembled on an ordinary mechanical press. It is meant to produce sheets with a hydraulic diameter of the openings of 17 – 25 mm. The change of the s_1/h_1 ratio is connected with the change in the step between the axes of the staggered slots, whereupon a change in the s_1 dimension is obtained, which affects the dimension h_1. Besides, the ambition is to maintain the degree of sheet expansion of about 1.6, i.e., the lengthening of the initial metal sheet to be about 60 %.

All of this gives an idea of a distribution of the effective area between this of the sheets and that of the empty space between them. Besides, the striving is for less metal to be put in, in order to obtain a packing with less specific weight. From technologic point of view, this creates conditions for increasing of the specific and effective area and for intensification of the mass transfer through tearing and renewal of the mass transfer surface, including that from the drops and jets flowing in the empty space. They additionally mix the liquid that flows on the lamellae and intensify the mass transfer.

CONCLUSIONS

This study describes the results of the research and implementation of horizontal expanded metal sheet packing, also called Holpack. The Holpack packing is made of expanded metal sheets placed horizontally at a certain distance from one another along the height of the apparatus. Its principle of operation, connected with the creation of a large phase surface area, created also in the empty space between the sheets, makes it quite effective. This is strengthened by the increased mass transfer as a result of the frequent tearing and renewal of interphase surface. It results in a low pressure drop, which creates favorable conditions for a large number of technological processes. The very good parameters, as regards the uniform gas and liquid distribution, approach the operation of the packing to the ideal conditions for performing heat- and mass transfer.

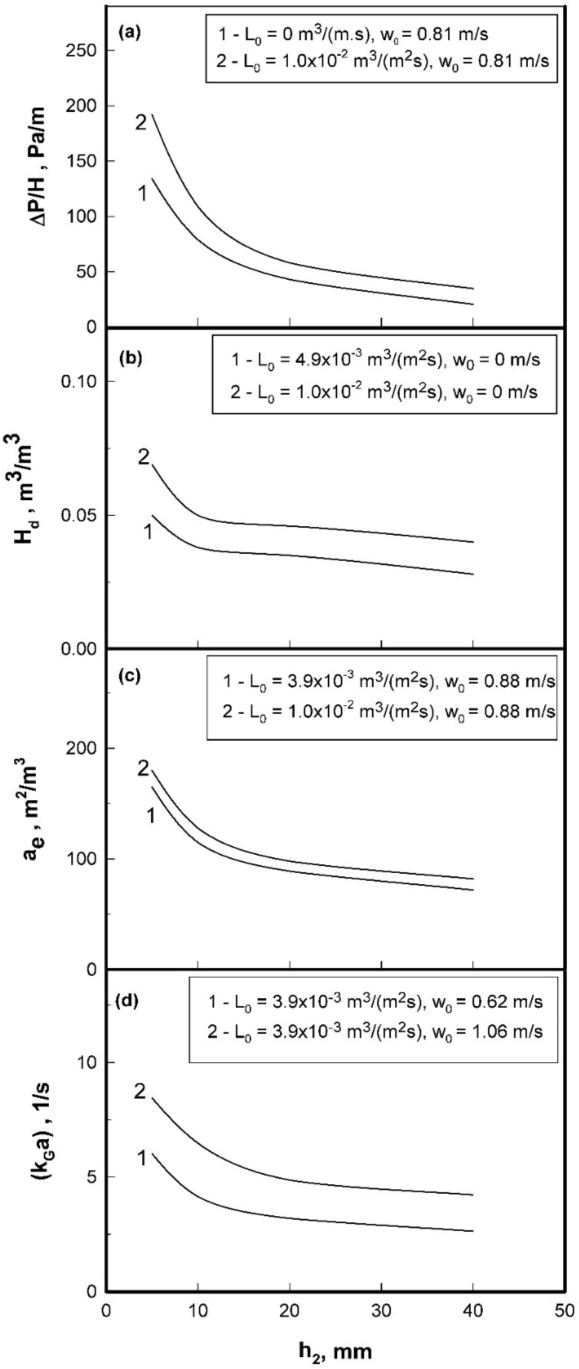


Fig. 18. Influence of the distance between the sheets of packings Nos. 1÷4 (Table 1) on: (a) Pressure drop, (b) Hold-up, (c) Effective surface area and (d) Mass transfer coefficient.

The detailed research of the hydrodynamic and mass transfer characteristics created a methodology for design of apparatuses for absorption, desorption, rectification and distillation processes and direct heat transfer. The industrial realization confirmed the effectiveness of the Holpack packing in apparatuses for chemical and food industry, power and environmental sectors.

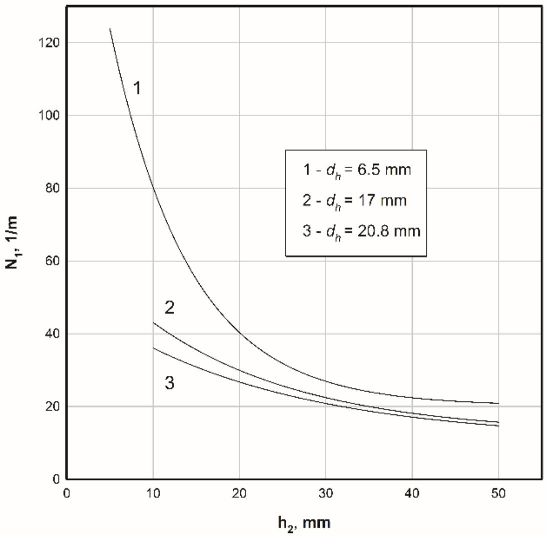


Fig. 19. Dependence of the number of the expanded metal sheets in 1 m height from the distance between them for Holpack packing (Table 1) for different hydraulic diameters of the sheet openings.

The experience gained from the realization of many projects opens up opportunities for improvement and intensification of the apparatuses operating with Holpack packing. The envisaged forthcoming steps are connected with variation of the proportions between some of the main dimensions of the sheets of expanded metal and optimization of the distance between them, according to the requirements of the concrete technological process.

Nomenclature

A - slit length of expanded metal sheet (Fig. 1), *m*;
a - packing specific surface area, m^2/m^3;
a_e - effective specific surface area, m^2/m^3;
B - slit longitudinal (longways) step of expanded metal sheet (Fig. 1), *m*;
C - slit transversal (breadthways) step of expanded metal sheet (Fig. 1), *m*;
C_1 - constant in Eq. (11);
c - oxygen concentration in water, g/m^3;
c_p - specific heat capacity, $J/(kgK)$;
D - diffusivity, m^2/s;
D_r - radial spreading coefficient, m;
D_c - column internal diameter, *m*;
D_{TL} - axial mixing coefficient (part of Bodenstein number) – Eqs. (12, 13), m^2/s;
d_h - hydraulic diameter of the slit, m;
$F = w_0\sqrt{\rho_G}$ - gas (vapour) capacity factor (F-factor), $kg^{1/2}/m^{1/2}$ s;
G - mass of the desorbed component per cross-section unit, $g/(m^2 s)$;
g - gravity acceleration, m/s^2
H - packing height, m;
H_d - dynamic holdup of the liquid phase, m^3/m^3;
HETP - height equivalent to a theoretical plate;
$HTU_L = \dfrac{k_L a_e}{L_0}$ - height of the (mass) transfer unit (HTU) for the liquid phase, m;
h - heat transfer coefficient, $W/(m^2 K)$;
h_1 - thickness of the expanded metal sheet (Fig. 1), m;
h_2 - distance between the expanded metal sheets (Fig. 1), m;
k - mass transfer coefficient, m/s;
$(k_G a) = k_G a_e$ - volumetric mass transfer coefficient for the gas phase, *1/s*;
$(k_L a) = k_L a_e$ - volumetric mass transfer coefficient for the liquid phase, *1/s*;
L - liquid superficial velocity, $m^3/(m^2 s)$;
M_f - gas maldistribution factor – Eq. (10);
MAE - mean arithmetical error;
MEA - monoethanolamine;
N_1 - number of expanded metal sheets per 1 m packing height, $1/m$;
NG - natural gas;
Q - liquid flow rate, m^3/s;
SD - standard deviation;
s - slit width of the expanded metal sheet (Fig. 1), m;
s_1 - lamella width of the expanded metal sheet (Fig. 1), m;
WFDR - wall flow deflecting ring;
w - gas (vapor) velocity, m/s;

Greek symbols

$\alpha = \lambda/(\rho c_p)$ - thermal diffusivity, m^2/s;

ΔP - pressure drop of packing, Pa;

ΔP_0 - pressure drop of dry packing, Pa;

δ - thickness of metal sheet (Fig. 1), m;

ε - volume void fraction of horizontal expanded metal packing, %;

ε_1 - free cross-section area of the expanded metal sheet, %;

λ - heat conductivity, $W/(mK)$;

μ - dynamic viscosity, $Pa.s$;

ν - kinematic viscosity, m/s^2;

ρ - density, kg/m^3;

σ - surface tension, N/m.

Subscripts

A - air;

G - gas phase;

L - liquid phase;

in - inlet value;

j - single jet;

max - maximum value;

out - outlet value;

0 - related to the overall cross-section;

w - related to the wall.

Superscripts

0 - excluded axial mixing value;

* - equilibrium value.

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