Inlet and Internal Devices for Packed Columns

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The uniform flow distribution in packed bed columns is very important condition for their efficient operation. This paper presents the basic requirements for design and construction of inlet and internal devices that ensure uniform flow of both liquid and gas phases along the whole height of packed-bed heat and mass transfer apparatuses. The results of author's studies and industrial experience are presented, as well as available literature data. Inlet devices for initial distribution and internals for redistribution of the liquid and gas phases, are described and discussed.

Keywords:
Packed columns, inlet devices, internals, distributors, maldistribution factor, wall effect

Introduction

Packed-bed columns are used in the chemical and food processing industry, power and environmental protection engineering. Their reputation is due to their high heat and mass transfer coefficients and low pressure drop.

Packed-bed columns demonstrate their features when operating in full countercurrent flow conditions. For this reason, a basic task in the design of such apparatuses is to create constant flow ratio in each part of the packing layer. Usually, it is obtained using appropriate input and internal devices for packed-bed columns.

The flows in an apparatus are never completely uniform. So, the aim is to obtain flow structure possibly near to the ideal replacement case, called plug flow. The real flow differs from plug flow for many reasons. For example, as it is known, the turbulence is characterized by chaotic velocity pulsations in all directions around a mean value. Fig. 1 shows apparatus schemes with different velocity profiles, and Fig. 1a shows only the longitudinal part of velocity vector. It is a typical case of gas movement in empty columns or in zones under a packing layer. As a result, some parts of the flow are forwarded with respect to the main flow, other parts are in arrears. A non-uniform flow rate profile over the apparatus cross-section is illustrated on Fig. 1b. In this case some flow particles leave the apparatus earlier, others – later. Fig. 1c represents an apparatus with circulation zones, where parts of flow remain longer than the main flow. The latter passes faster through the apparatus without crossing the whole cross-section, where circulation zones and, even, stagnant zones are formed.

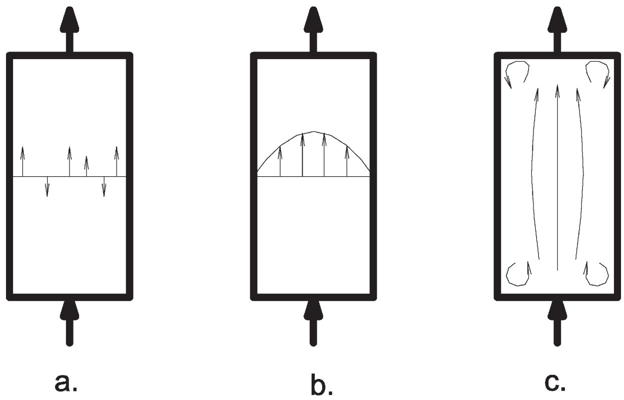

Fig. 1 – *Schemes of apparatuses with different velocity profiles*

It is evident that the mass and heat transfer processes that depend on flow rate, proceed with different intensity in different apparatus zones. For example, in the stagnant zones process intensity is rather low and the mass transfer is done mainly by diffusion.

The aim of this paper is to show the ways for creation of flow rate uniformity and to describe the necessary inlet devices and internals. Devices from literature sources and own developments, are considered.

Liquid feed distributors

The distribution of liquid flow rate over the cross-section of packed-bed columns is very important for their efficient operation.[1–3] Common designer practice is to care about the uniform distribution only at the entrance of packing layer, ignoring the situation in the packing volume. However, the liquid flow rate changes its distribution due to many

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reasons: irregularity of packing structure, tendency of formation of flow towards the apparatus wall, influence of gas stream irregularities, etc.

Many types of devices for initial uniform distribution are designed and tested.[1–10,43] The majority of them use the principle of creation of large number of single rivulets (Fig. 2) with small inrush, thus eliminating the possibility of formation and carrying away of drops. In this case, the determination of the necessary number of irrigation points and the manner of their location is very important.

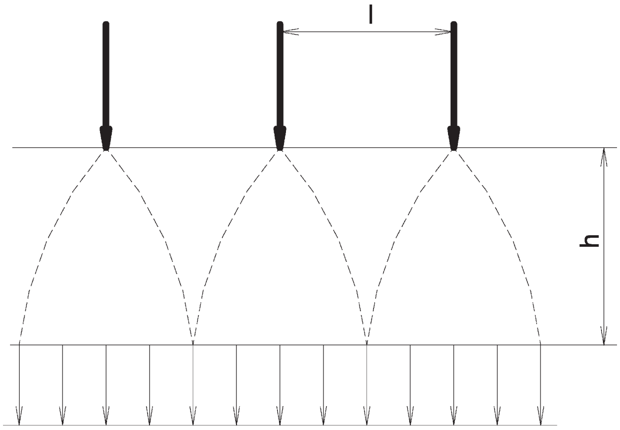


Fig. 2 – *Scheme of point irrigation*

We have studied the spreading ability of the upper part of packings, which is defined by its spreading coefficient D.[11–15] We have derived a simple relation for determination of the height / depth of a packing layer, necessary to supply uniform distribution at point irrigation, triangle location of the trickles and distance l between them

$$h = 0.11 \cdot l^2 / D\,, \tag{1}$$

The modern columns usually operate at rather high superficial velocity, at F-factor about 1.8 – 3 m s^{-1}. It requires small pressure drop of the used irrigation devices. This is the main reason for creation of irrigation devices with reflecting baffles.[10]

The liquid is fed through a system of pans (Fig. 3). The surface below the pan is irrigated through bottom holes or overfill pipes. Also, the pan sprinkle lateral streams towards reflecting baffles. The reflectors are made as thin sheets that do not practically reduce the apparatus cross section. Many arrangements of irrigation points can be realized, the distance between them being determined in most cases by Eq. (1). This device can operate with liquids containing solid particles. In this case, the holes and overfill pipes are mounted at some height over the pan bottom, in order to allow impurity sedimentation.

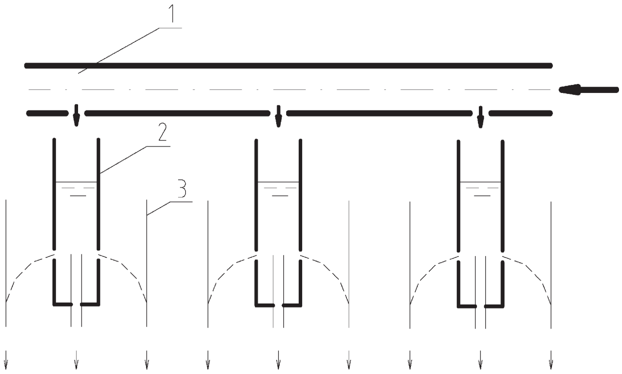


Fig. 3 – *Principal scheme of irrigator with reflectors 1 – tube, 2 – pans, 3 – reflector*

Fig. 3 illustrates the design of irrigator with reflectors. The liquid enters by a tube or a pan 1 towards the distribution pans 2 in a quantity enough to feed the whole irrigator. Spreading over the packing is done through lateral holes and vertical pipes. The jet has to reach the reflector 3 and pour over it without breaking down in drops, in order to avoid drop holding by the gas flow rate. When the liquid is flowing out through a circle orifice at constant head H, not higher than 3–4 m water column, the jet trajectory (Fig. 4) is described by a parabolic equation

$$y = x \operatorname{tg}\theta \pm \frac{g x^2}{2v^2 H \cos^2\theta} \tag{2}$$

Introducing in (2) $v = \varphi\sqrt{2Hg}$ and jet flight distance ρ expressed as the horizontal projection of jet trajectory from the orifice till the contact point

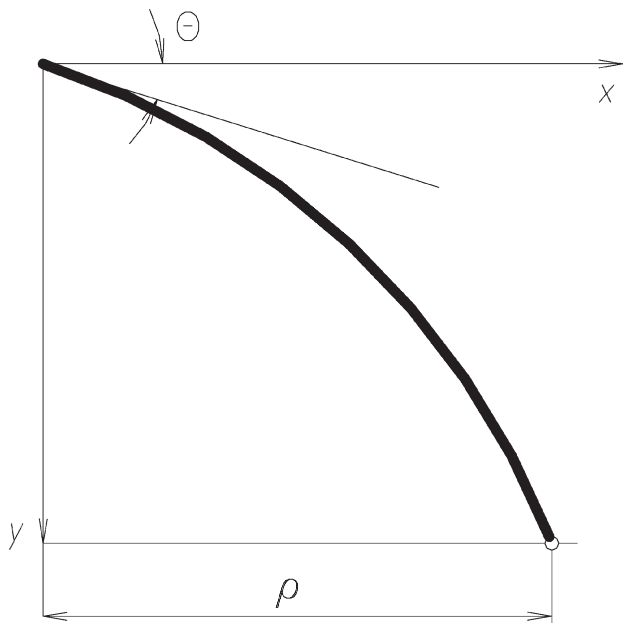


Fig. 4 – *Scheme of liquid jet (trickle) trajectory*

with horizontal plane (see Figs. 3 and 4), Eq. 2 becomes

$$y = \rho \operatorname{tg}\theta \pm \frac{\rho^2}{4\varphi^2 H \cos^2\theta} \tag{3}$$

Eq. 3 describes accurately the trajectory of a consolidated liquid jet not affected by a countercurrent gas stream.

Generally, the orifice axis is horizontal ($\theta = 0$), and Eq. 3 is reduced to

$$y = \frac{\rho^2}{4\varphi^2 H} \tag{4}$$

The dimensioning of this type of liquid irrigator is simple and is applicable even in case of large apparatus cross-section.[2,10] The maldistribution is low, e.g. it is ±3.5 % in an apparatus with cross-section of 9 m^2.[16]

The liquid distribution in apparatuses with diameter till 2.5 m can be done with a nozzle. This device has simple and compact design that does not create additional resistance to gas flow. Small amount of metal is needed for its manufacture, and the liquid distribution is relatively uniform.[2] In spite of all qualities, the nozzles do not assure enough initial flow uniformity. Literature data, as well as our results, select jet-vortex nozzles (Fig. 5) as the best.[17] They have a body with incorporated vortex creator – central circle orifice and peripheral rectangular channels in the form of four-thread worm. The jet is dispersed as a result of hitting of central and tangential flows.

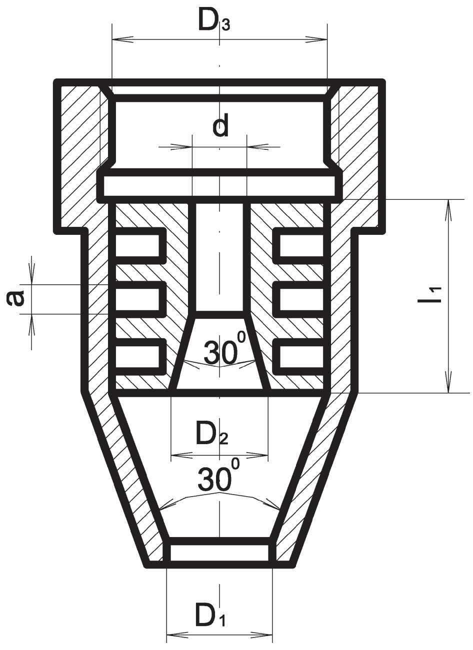


Fig. 5 – *Jet – vortex nozzle*

The nozzle has to be mounted strictly in vertical position in the apparatus upper part at the column axis. The jet is dispersed at angle of 90°. Relatively uniform distribution has been obtained over the whole cross-section for a distance between the nozzle and packing smaller or equal to apparatus radius. The expression relating flow rate, size of nozzle orifice D$_1$, and pressure drop has the form.[17]

$$Q = \frac{\pi D_1^2}{4}\sqrt{2g\Delta p}\cdot\varphi\cdot 3600 \tag{5}$$

The other nozzle dimensions are determined on the base of orifice diameter ($d = 0.5\ D_1$; $a = 0.4\ D_1$; $D_2 = D_1$; $D_3 = l_1 = 2\ D_1$).

In order to improve the uniformity of the nozzle irrigator, a device is developed[18] for correction of flow distribution according to nozzle characteristics. The latter are defined by the pressure drop and related nozzle capacity. Generally, the distribution is uniform in rather large range of pressure drop (0.5 – 4.5 bar).

This redistributor (Fig. 6) is to be used in columns of small and medium diameters.[18] It consists of coaxial cylinders 3, small in height, with serrated down edges aimed at avoiding of eventual shifting of the trickles. The redistributor is placed just over the packing in strictly horizontal position at a column radius distance from the nozzle. The coaxial

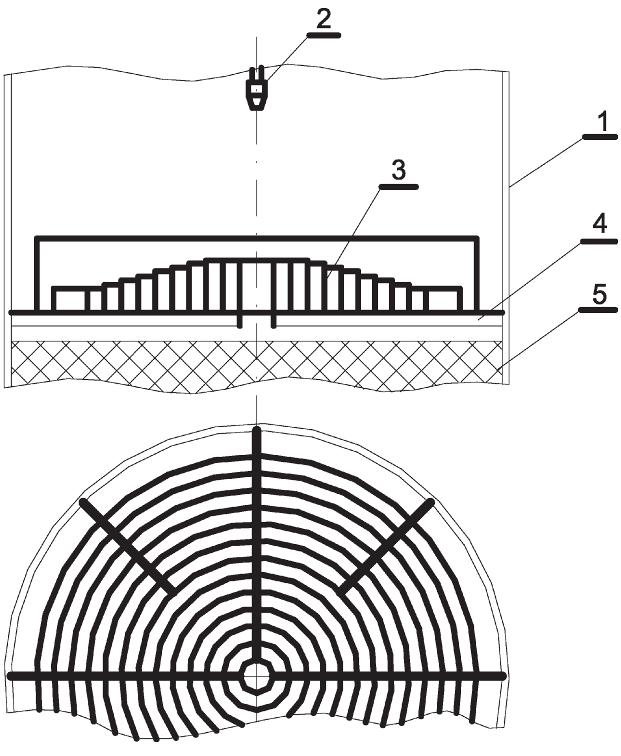


Fig. 6 – *Scheme of redistribution device for a column 1400 mm in diameter. The main nozzle parameters are given on Fig. 5: 1 – Apparatus body, 2 – nozzle, 3 – redistribution device, 4 – fixing strap, 5 – packing*

cylinders have different heights defined in a manner to ensure for each cylinder the same quantity of liquid as for its neighbors.

Fig. 7 illustrates nozzle liquid distribution over the packing in a column of diameter 1400 mm without (1) and with (2) redistribution device. Strong equalizing ability of the tested redistributor is seen. The irrigation density is measured at a distance of a column radius below the nozzle orifice using calibrated vessel. Samples are taken over two perpendicular diameters of the column cross-section, and the results are averaged over several measurements.

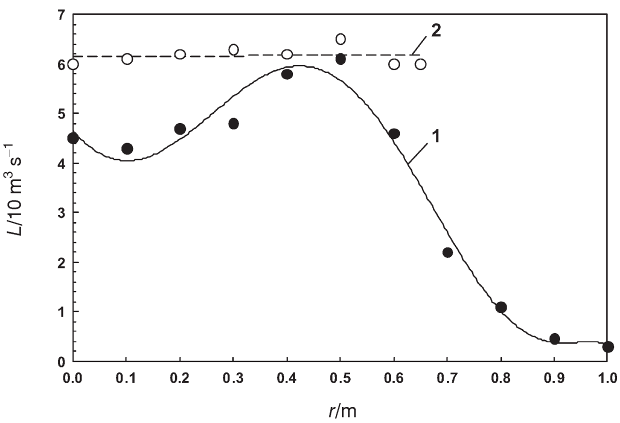


Fig. 7 – *Distribution of irrigation density over the cross section of a column 1400 mm in diameter without (1) and with (2) redistribution device (3), shown on Fig. 6.*
1 – Δp = 1.3 bar; Q = 27 m^3 h^{-1}; 2 – Δp = 2.1 bar; Q = 35 m^3 h^{-1}

Industrial tests have shown that the described nozzle with redistributor can be successfully used for uniform liquid distribution in cylindrical packed-bed columns of 400 – 2000 mm at nozzle pressure drop 0.5 – 4.5 bar. The irrigator's own surface is small enough and does not block the apparatus cross-section.

Liquid redistributors

The initial liquid distribution over the column cross-section is changed because the liquid is flowing preferentially towards the column wall, thus enlarging the wall flow. Consequently, the ratio of gas and liquid flows is different for the packing bulk and for wall region, which affects the process driving force. The wall flow rate increases along the packing height and can attain 60 % (Fig.8) depending on packing type and dimension.[22] Consequently, measures for its redistribution should be taken.[20,21]

There are different theories for the process of formation and increasing of wall flow. We have proposed an approach,[20] which assume that the

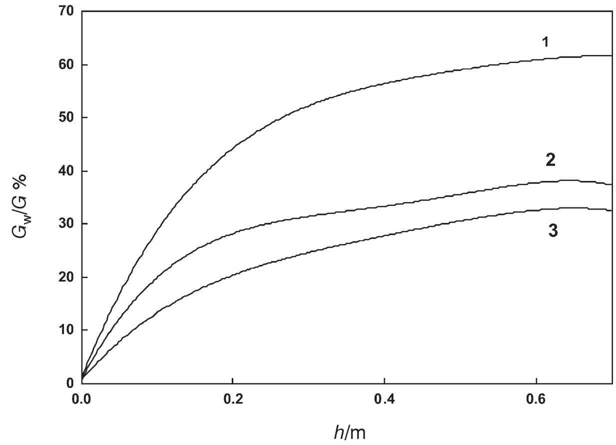


Fig. 8 – *Wall flow as depending on packing height. Packing of ceramic Raschig rings: d = 1 – 1.5 cm, v_L = 5 m^3 h^{-1} m^{-2}; d = 2 – 2.0 cm, v_L = 20 m^3 h^{-1} m^{-2}; d = 3 – 3.0 cm, v_L = 20 m^3 h^{-1} m^2.*

packing elements located randomly in the wall zone collect the liquid from a larger surface and direct it to the wall thus creating wall flow. The flow in opposite direction is smaller, because in most cases the packing elements contact the wall in points, not enough to ensure equivalent flow back from the wall.

The problem can be resolved by mounting of redistribution rings with small width (of the order of a packing element dimension) placed along the column wall.[20,21] They redirect the wall flow back to the packing, eliminating bypass flows that can substantially worsen some processes. The small width of the rings does not affect apparatus pressure drop. Other types of wall redistributors are reported in the literature.[3,9,20] The proposed rings have more sophisticated form, e.g. with "beaks" penetrating deeper in the column in order to lead away the wall flow at larger distance from the wall.

We have studied how the wall flow and HTU depend on packing type, layer height, irrigation density, and distance between the reflecting rings.[21] A column of 190 mm in diameter has been equipped with 5 mm wide reflecting rings on its wall. The wall flow has been measured by a ring vessel that collects the liquid flowing till 5 mm away from the column wall. The tests have been done with several types of horizontal packing of expanded metal sheets (Holpak).[12,19,21,24,34,39] Some results are given on Figs. 9 and 10.

It is shown, that almost complete elimination of wall flow is obtained with reflecting rings placed at 100 mm distance (Fig. 9). At 200 mm, HTU in the wall zone and in packing bulk are practically identical (Fig. 10), i.e. good uniformity is attained even at larger distance between the reflecting rings.

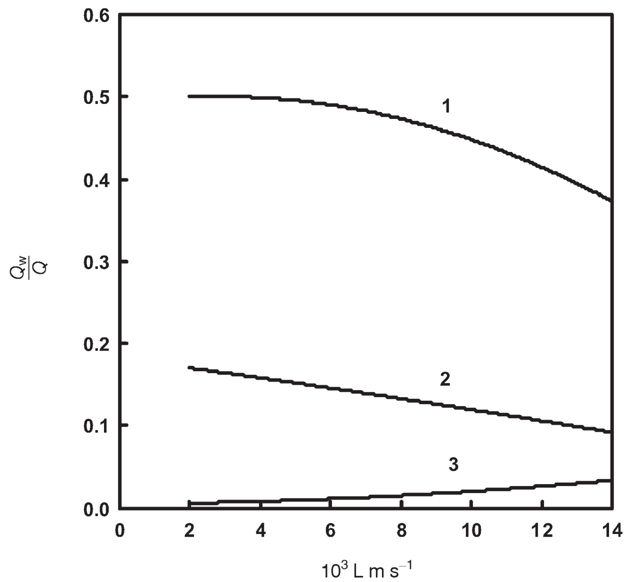


Fig. 9 – *Influence of the irrigation density on wall flow at various distance between the reflecting rings. 1 – no rings; 2 – distance between rings 200 mm; 3 – distance between rings 100 mm*

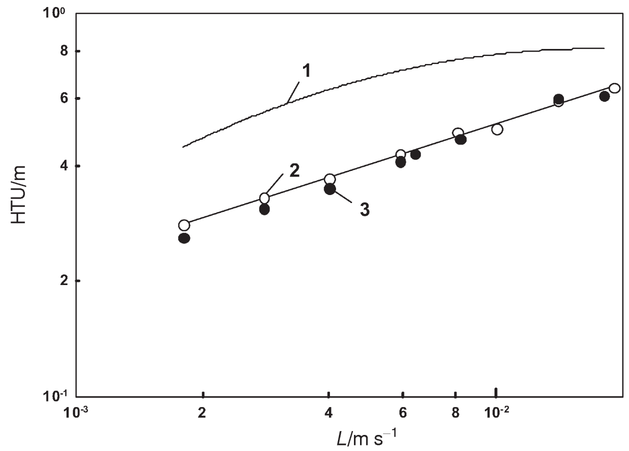


Fig. 10 – *Influence of irrigation density on the height of transfer unit for expanded metal sheets horizontal packing (Holpak). 1 – in the wall zone without redistribution rings; 2 – in the wall zone with rings placed at 200 mm from each other; 3 – in the bulk of packing*

Consequently, 200 mm distance is enough to eliminate the unfavorable influence of wall flow.

The case with arranged packings is similar. Although their structure is regular, it is more difficult to achieve enough packing density in the wall zone, and special precautions have to be taken. For example, MONTZ[9] proposes special elements for denser wall zone and other devices for redirection of wall flow, similarly to reflecting rings.

The function of redistribution devices is to collect the wall flow in order to irrigate uniformly the next packing layer. Although different designs are known,[3–6, 9,23,43] all of them use inclined plates to direct the flow to pans where it is collected and fed to irrigator.

We have successful experience in this field. We have used a cascade of several truncated cones below the packing layer in order to collect the liquid without significant reduction of apparatus cross-section. The collected liquid has been uniformly distributed over the next lower packing layer with irrigator of type already described above. A column of diameter 400 mm has been filled with horizontal packing of expanded metal sheets Holpak (8 400 mm total height), divided in three layers with two redistribution devices between them. The apparatus has been operating as stripping column for elimination of chloroform from waste water. The tests have shown very high efficiency, up to 400 000 times reduction of chloroform contents.[24] These results are due also to application of redistribution devices.

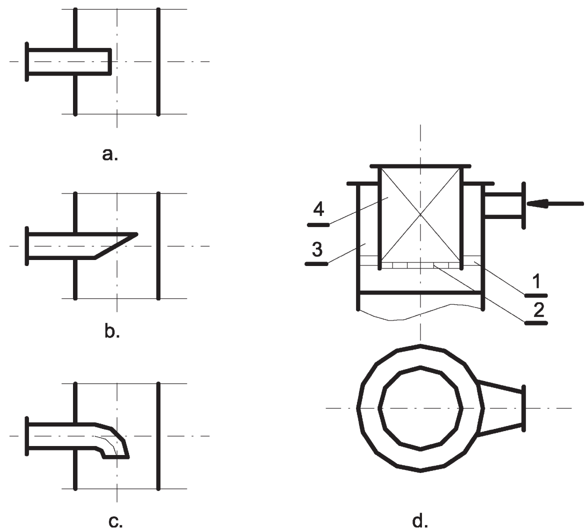
Gas distributors and redistributors

Until recently it was presumed that the gas velocity profile in a packed bed quickly becomes uniform because of layer pressure drop. This statement follows from investigations on gas distribution in layers with small voidage used mainly in catalytic apparatuses. Similarly to them, the old-fashioned packings made preferably of ceramics have lower voidage. The modern packings for operation at high velocity have large free volume and appropriate form in order to ensure good conditions for highly efficient heat and mass transfer processes. They are used for treatment of large gas flows, for example in technological gas purification or waste gas treatment for environmental purposes.

However, the modern packings have lower gas distribution ability because of their small pressure drop. The initial gas distribution is kept along the layer height. For this reason, special precautions have to be taken for obtaining a uniform initial gas distribution.

Studies of input gas devices[25–35] have revealed that the commonly used inlets for lateral feeding right at the column wall or inside the column, sloped or not (Fig. 11 a, b), provide non-uniform distribution. Because of its high velocity, the gas stream hits in the opposite wall resulting in vortex formation and back gas flows in the zone of supporting grid.[32,35] These phenomena create increased initial maldistribution. For better distribution, it is recommended to place the inlet at a distance (0.15 – 0.18) D_a from the packing layer bottom (D_a is apparatus diameter).

Some improvement of the velocity profile can be obtained by gradual enlargement of the inlet pipe

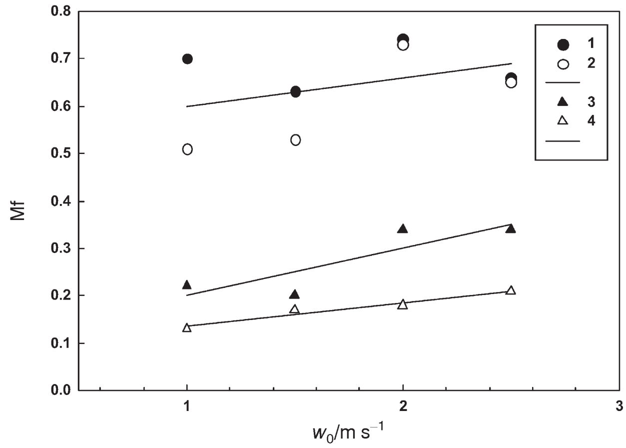


F i g . 1 1 – *Various types of gas inlets (GI): (a) straight inlet; (b) slope inlet; (c) bend inlet; d – circular inlet; 1 – gas distributing lattice; 2 – supporting grid; 3 – annular chamber; 4 – packed bed.*

in the column according to aerodynamic rules and keeping the distance from the packing as already recommended. Our study with ceramic honeycomb packing[14,15] in industrial apparatus for direct heat transfer[36] has shown that maldistribution factor Mf = 0.155, can be attained. The value is near to the irregularity created by this kind of packing.

Fig. 11 illustrates various gas inlets for common use.[33,39] The maldistribution factor Mf at various gas flow velocity is shown on Fig. 12 for different inlet design. The maldistribution factor is defined as mean quadratic difference of local and superficial velocity:

$$Mf = \sqrt{\frac{1}{n}\sum_{n}\left(\frac{v_{G_i} - v_{G_0}}{v_{G_0}}\right)^2} \tag{6}$$



F i g . 1 2 – *Influence of the type of input gas device and gas velocity on the initial maldistribution below a layer of 0.26 m honeycomb packing: 1 – straight inlet (Fig.11a); 2 – slope inlet (Fig.11b); 3 – bend inlet (Fig.11c); 4 – circular inlet (Fig.11d).*

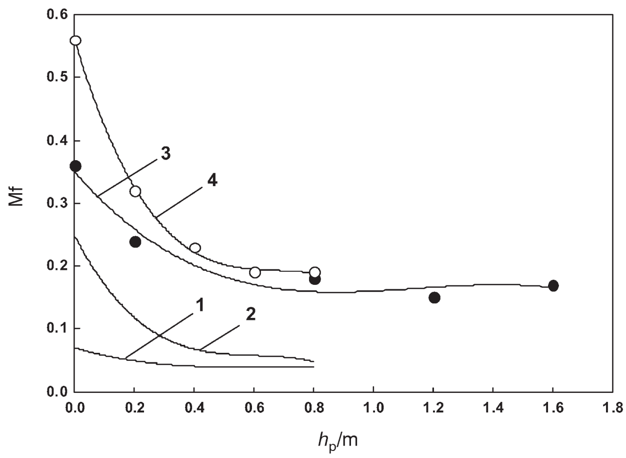
where v_{G_i} and v_{G_0} are respectively local and superficial velocity, n is number of measuring points.

The study is carried out with a column 470 mm in diameter. For three cases shown on Fig. 11a, b, c, the ratio of inlet and column cross sections S_0/S_k = 0.23. The device on Fig. 11 d feeds the gas from a circular chamber 3 to packing layer 4 by two consequent gas-distributing lattices with free section 50 % for the first one and 25 % for the second.[34]

Four gas inlet devices have been compared by measurements of velocity profiles below and above a layer of 0.26 m honeycomb packing. This height was chosen to ensure calming of turbulent pulsations at relatively low pressure drop in order to perform correct velocity profiles measurements. The inlets on Figs 11 c, d provide better distribution. In case of bend inlet (Fig. 11 c), the gas stream directed downwards meets the column bottom or liquid mirror. Some energy dissipation takes place resulting in equalizing of velocity profile. The best is the circular inlet (Fig. 11 d) with gas distributing lattices that generate the most part of device pressure drop.

Fig. 12 demonstrates that the gas distribution depends, although not very strongly, on gas flow velocity. This conclusion is confirmed also in our papers.[37,38]

Analogous studies by other authors[28] lead to similar conclusions. Maldistribution factor data for metal packing Mellapak Y250 in a column of 1 m in diameter is shown on Fig. 13. The gas inlets are similar to those of Fig. 11 (curves 1 and 2). Fig. 13 represents also our results for ceramic honeycomb packing in a column 0.47 m in diameter and packing height up to 1.6 m. The experiments have been



F i g . 1 3 – *Maldistribution coefficient at various heights of packing layer, different gas inlets, packings and flow velocity. 1 – inlet (a), packing Mellapak 250Y, w_o=2.85 m s^{-1} [28]; 2 – circular inlet, packing Mellapak 250Y, w_o=2.78 m s^{-1} [28]; 3 – bend inlet (c), honeycomb packing, w_o = 2.5 m s^{-1}; 4 – straight inlet (a), packing Holpak, w_o = 1.8 m s^{-1}.*

carried out at four different gas (air) flow velocities without liquid phase. Local maximal velocities have been measured over each hole of the packing elements.

It is seen that the inlet type affects the gas maldistribution only with thinner layers. After some limit packing height, the maldistribution factor attains a value called uniformity limit[37–39] that depends only on packing type. The type of input device and its rate of uniform distribution is very important in case of packings with low pressure drop, e,g. high efficient plastic packing Turbo-Pack with large free surface.[40,41]

Combined distribution of gas and liquid flows

Readings on this subject are rather limited. Some company prospectus materials[9] and literature sources[24] propose the idea for several packing layers separated by devices for redistribution of, both, liquid and gas flows. It is assumed that liquid flow distributors can be arranged to serve also as gas distributors. Indeed, even when cutting packing layer in parts in order to mount liquid distributors, a possibility for radial gas flow is created, which is a form of gas redistribution.

Schultes[42] have published a design that ensures uniform distribution in both phases of distillation process, resulting in real process operation rather near to theoretical one (Fig. 14). In this case, good distributing devices in the upper end (for liquid) and in the lower end (for vapors) are used in combination with redistribution devices along the apparatus. In the liquid feeding zone, the redistributor is combined with irrigator for the liquid phase fed (R_F).

The device on Fig. 15 is our patented solution for gas/liquid redistributor.[23] The liquid below a packing layer is collected and led to a perforated tray 2. Here the heat and mass transfer processes continue at very good phase mixing, because the gas flow through a liquid layer on the tray, thus being redistributed over the cross-section. V-shaped barriers 3 of expanded metal sheets in the upper part ensure operation at large gas/vapor flow rate (F-factor till 5). Passing through overflow device 4 and pipe 5, the liquid goes to the irrigator for uniform distribution 6 over the next layer. The advantages of this device are in creation of conditions for radial distribution of both phases combined with intensive mixing of collected liquid with the gas flow.

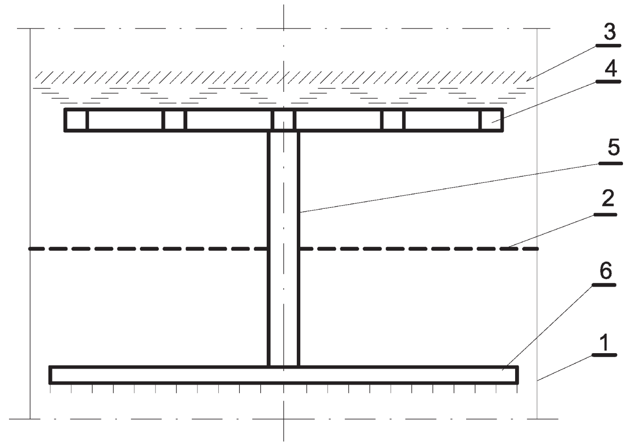


Fig. 15– *Combined redistribution device for gas/vapors and liquid. 1 – column, 2 – perforated tray, 3 – V-shaped barriers, 4 – overflow device, 5 – pipe, 6 – liquid distributor*

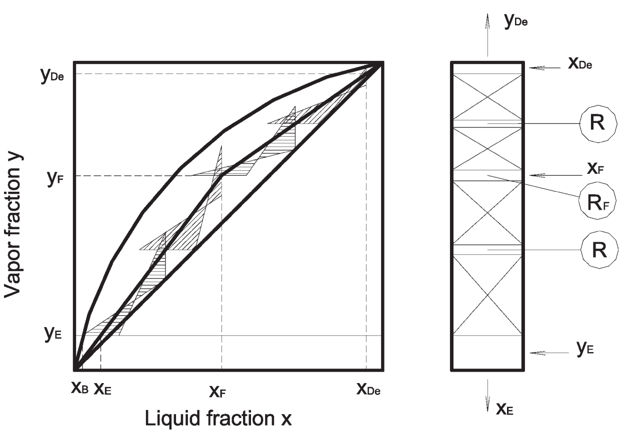


Fig. 14– *McCabe-Thiele diagram with redistributors /R/ and variations of v_{ir}/v_L ratio.*

Conclusion

Analyzing our results and literature sources, it can be concluded that the flow uniformity in packed-bed columns is very important condition for their efficient operation. We have found that apparatuses filled with modern highly efficient packings lose their advantages in absence of good flow distribution. For this reason, the design and construction of heat and mass transfer packed-bed apparatuses should be done with special attention not only to initial flow distribution, but also to measures for keeping its radial uniformity along the packing height, especially in case of higher packing layers.

Nomenclature

a, d, D_1, D_2, D_3 – dimensions on Fig. 5

D – distribution coefficient , m

D_a – apparatus diameter , m, mm

S_o – inlet cross section , m^2

S_k – column cross section ,m^2

G – general volume flow rate , $m^3 s^{-1}$
G_w – liquid flow rate on the wall, $m^3\ s^{-1}$
g – gravity acceleration, $m\ s^{-2}$
h – height of the redistribution packing layer, m
H – hydrostatic pressure, m H_2O
h_p – height of packing layer, m
HTU – height of a transfer unit, m
l – distance between irrigation points, m
l_1 – dimension on Fig. 5
v_{ir} – irrigation density flow rate, $m\ s^{-1}$
Mf – maldistribution coefficient /factor
n – measuring points
Δp – pressure drop, bar
Q – liquid flow rate, $m^3\ h^{-1}$
r – radius, m
R – gas/vapors and liquid redistributor
R_F – redistributor of gas/vapors and liquid combined with irrigator for liquid phase fed
v_L – liquid velocity, $m\ s^{-1}$
w_i – local gas velocity, $m\ s^{-1}$
w_o – gas superficial velocity, $m\ s^{-1}$
x, y – space coordinates
X, Y – liquid and vapor phase respectively on Fig.14

Greek letters

φ – coefficient
θ – angle illustrated on Fig. 4 (Eqs. 2 and 3)
ρ – dimension on Fig. 4

Subscripts

De – distillate
E – entrance
F – feed
G – gas
L – liquid

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