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Height of vertical plates with inclined capillary grooves for a redistribution packing layer of packed columns

D. Dzhonova-Atanasova, D. Kolev, N. Kolev

Institute of Chemical Engineering, Bulgarian Academy of Sciences, "Acad. G. Bonchev" Str., Bl.103, 1113 Sofia, Bulgaria

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The uniform distribution of the liquid phase over the cross-section of a packed column is a major prerequisite for its effective operation. Regarding various distributor designs, the best uniformity is achieved with devices where the liquid is divided into jets with equal flow-rates. The final liquid redistribution, to obtain uniformity over a cross-section area of the size of a packing element, takes place in the packing itself or in a specially designed redistribution layer. For this purpose a new packing, especially proper for low liquid superficial velocity has been developed and investigated. It consists of parallel vertical polystyrene plates with inclined crossing capillary grooves stamped on them. A computer procedure has been developed for calculating the height of the redistribution layer for a distributor with a given distance between the feed points. The calculated height ensures, with a selected precision, equality of the flow-rates of the liquid phase leaving the capillary grooves. The comparison with other devices shows that for a given degree of uniformity, the new packing is characterized by significantly smaller height.

Key words: packed columns, liquid distribution, redistribution layer height, capillary grooves, liquid flow-rate, radial liquid spreading coefficient

1. INTRODUCTION

Of all existing packing designs, the packings with vertical walls and especially the honeycomb packings [1-3] are characterized by the lowest pressure drop for a mass transfer unit, but have bad liquid distribution properties. With the purpose to operate as a redistribution layer over a basic layer of this type of packings, a new packing is developed and investigated [4-7]. It consists of vertical polystyrene plates with crossing inclined capillary grooves stamped on their surface, especially proper for low liquid superficial velocity. Changing only the direction of the liquid phase by adding a horizontal component to its velocity vector, it avoids the disadvantage of the existing redistribution packings with inclined walls [8-10] to turn also the direction of the gas flow which leads to increasing of the pressure drop.

The plates can operate as a redistribution layer between the distributor and the main packing and also as a part of the liquid distributor. A scheme of such a device is presented in Fig. 1. The liquid phase leaves the pipes (troughs) (1) of the distributor through orifices perforated in them and runs over plates (2). Here it is regularly distributed by the inclined crossing capillary grooves. From plates (2) the liquid flows over plates (3) and is regularly distributed by the grooves. The uniform distribution after plates (2) and (3) ensures regular distribution over the whole apparatus cross-section. Fig. 2 is a photograph of a sample plate with stamp inclined grooves.

For implementation of the new device in the industry, it is necessary to have a method for calculation of the height of the plate under which the distribution of the liquid phase will be uniform with a preliminary given precision.

The aim of the present work is to propose a calculation procedure for determination of the height of the new redistribution layer at a given distance between the feed points and degree of uniformity and to compare the new packing design with the existing.

2. CALCULATION PROCEDURE

2.1. Calculation equations

Fig. 3 shows a scheme of the capillary grooves on the surface of the vertical plate between two feed points A and A_1. Here l, m, is distance between the feed points. The liquid from a feed point flows down and is divided into the grooves (shown by arrows). The flow between each two drip points is symmetrical in respect to the axis A'B'. That is why the calculations are performed only for one of the symmetrical parts, i.e. the grooves between lines AB and A'B'.

*To whom all correspondence should be sent:
E-mail: : dzhonova@bas.bg

The proposed procedure for calculation of the flow-rates in each part of the grooves uses the following equations.

1. Equation of the material balance at a crossing point with coordinates x_i , y_j :

$$V_{i,j} + U_{i,j} = V_{i-1,j+1} + U_{i-1,j-1} \qquad (1)$$

where $U_{i,j}$ and $V_{i,j}$ are the outgoing flow-rates in m^3/s in direction from line AB to A'B' and from line A'B' to AB respectively (Fig. 3) at a crossing point with coordinates (x_i,y_j). The beginning of the accepted coordinate system is in the feed point A. The computations are made in discrete points with vertical distance between them $\Delta x=x_i-x_{i-1}$, and horizontal distance $\Delta y=y_j-y_{j-1}$ in m, Fig. 3, in the calculation region AA'B'B, $i=0\div m$, $j=0\div n$ are current numbers of steps along x and y axis respectively, where m and n are the respective maximal numbers of steps.

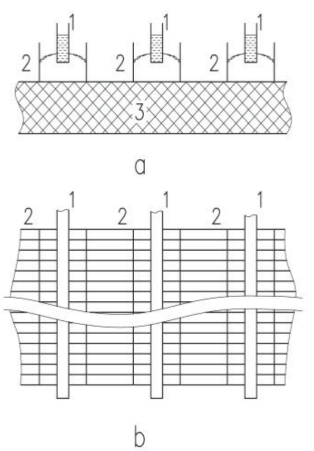

Fig. 1. Liquid phase distributor including plates with inclined crossing grooves. (a) Cross–section view; (b) Above view; (1) Distributing pipes (troughs); (2) Distributor plates with grooves; (3) Redistribution layer plates with grooves.

Fig. 2. Polystyrene packing plate with stamped inclined capillary grooves.

2. Equation for the maximal flow-rate in a capillary groove, just below the drip point A (in Fig. 3), where $i=j=0$, [7]:

$$Re_{max}=0.07\, Ga^{0.79}\, (\sin\alpha)^{0.94}, \qquad (2)$$

where α is the groove inclination angle, Fig. 3; $Re_{max}=U_{max}/\nu d_h$ is Reynolds number of the flow in the part of the groove just below the feed point; d_h is the hydraulic diameter in m, defined as $d_h=4ab/(2b+a)$, where a and b are the groove width and depth in m; U_{max} is maximum flow-rate in the parts of the groove just under the feed point, m^3/s; ν is kinematic viscosity, m^2/s; $Ga=gd_h^3/\nu^2$ is Galilei number; g is gravity constant, m/s^2.

3. Equation for the outgoing flow-rates at the crossing points on line AC, where $i=j$ and the flow-rates $V_{i-1,j+1}=0$, [7]:

$$\frac{U_{i,j}}{U_{i-1,j-1}} = 0.71\,Ga^{-0.17\left(\frac{U_{i-1,j-1}}{U_{max}}\right)+0.14(\sin\alpha)} \times Re_{i-1,j-1}^{\,0.38\left(\frac{U_{i-1,j-1}}{U_{max}}\right)-0.31(\sin\alpha)} \qquad (3)$$

$Re_{i-1,j-1} = \dfrac{U_{i-1,j-1}}{\nu\, d_h}$ - Reynolds number in the groove between points (x_{i-1},y_{j-1}) and (x_i,y_j).

4. Equation for the outgoing flow-rates at the crossing points under line AC, where $i\neq j$ and the flow-rates $V_{i-1,j+1}>0$:

$$\frac{U_{i,j}}{U_{i-1,j-1}+V_{i-1,j+1}} = 0.5\left[0.53\,Ga^{0.09(\sin\alpha)} \times Re_{i-1,j-1}^{\,0.06\left(\frac{U_{i-1,j-1}}{U_{max}}\right)} (\sin\alpha)^{-0.4}\right]^{\frac{U_{i-1,j-1}-V_{i-1,j+1}}{U_{max}}} \qquad (4)$$

At the boundaries of the calculation region:

1. Initial point A: $U_{0,0} = Q/2$, where Q is flow-rate at a feed point, m^3/s;

2. Axis of symmetry, line AB: $U_{i,0}=V_{i-1,1}$ – perfect deflection;

3. Line CB' $V_{i,n}=U_{i-1,n-1}$ - perfect deflection. To have flow symmetry for the end points next to the column wall, the distance between the plate vertical edge and the closest feed point is equal to 1/2 AA_1 and the end grooves are stopped.

4. Line AC $i=j$: $V_{i-1,j+1}=0$, $U_{i,j}$ calculated by Eq. (3).

Inside the boundaries of the calculation region $U_{i,j}$ is calculated by Eq. (4)

Assumptions

1. $Q=2U_{max}$, i.e the liquid flow-rate at the drip point is chosen equal to the maximum flow-rate the first channel is able to take up according to Eq. (2)

without liquid overspilling. Although the calculation results presented are obtained with this assumption, the proposed calculation procedure gives the possibility to use larger flow-rates at the drip point with overspilling and taking the liquid by the channels situated downwards.

2. Eqs. (3) and (4) are obtained in [7] by processing experimental data for which

$$\frac{U_{i,j}}{U_{max}} \geq 30\% \qquad (5)$$

This ratio is used to characterize the filling up with liquid of the groove cross-section. The smaller is the liquid flow-rate in the groove, the smaller is the degree of its filling up with liquid and the greater the possibility for the liquid to be completely drawn out in the crossing groove. It means that different equations describe the data for different extent of filling up.

3. Eqs. (2) and (3) are proved only for laminar hydrodynamic regime [7].

Variants of plate design

1. To get round the constraint for laminar flow, at turbulent regime conditions the single groove can be replaced by several parallel channels of smaller hydraulic diameter, which ensures laminar regime in each of them.

2. To ensure a greater degree of filling up of the grooves with liquid satisfying Eq. (5), for an industrial packing the dimensions of the groove cross-section can be reduced downstream of a given row of crossing points**.** At the same time, reduction of the groove depth will reduce the packing pressure drop.

3. To increase the number of the drip points after the redistribution plate, the number of the channels can be redoubled after achieving a given degree of uniformity at a row of crossing points (plate design in Fig. 2). The reduction of the distance between the crossing points at a given inclination of the grooves leads to increasing of the necessary height of the vertical plate for obtaining a prescribed degree of uniformity, which follows from the distribution model of Tour and Lerman [11].

2.2. Steps of the calculation procedure:

1. Input data:

- angle of inclination of the grooves α;
- steps between the crossing points Δy, $\Delta x = \Delta y.tg\ \alpha$;
- groove width and depth, a and b;
- distance between the feed points, l;
- physico-chemical properties of liquid phase;
- flow-rate at the feed point Q dependent on the liquid superficial velocity and the number of the drip points of the distributor per unit of the column cross-section.

2. Calculating the flow-rates $U_{i,j}$ and $V_{i,j}$ successively in each crossing point of a given horizontal row on the plate using their values determined at the previous horizontal row of crossing points $U_{i-1,j-1}$, $V_{i-1,j+1}$, by Eq. (1)-(4) with the relations at the boundaries.

3. When at a certain crossing point condition Eq. (5) is not fulfilled, the groove hydraulic diameter is reduced preserving the ratio between the groove depth and width. The reduced diameter is determined by $d_h' = d_h\left(\frac{U'_{max}}{U_{max}}\right)^{0.297}$ following from Eq. (2), where $U'_{max} = U_{i,j}/0.3$, $U_{i,j}$ is the flow-rate at the current point. It is assumed that $d_h = d_h'$ downstream of the current row of crossing points with coordinate x_d, i.e. for $x \geq x_d$ (down the dashed line in Fig. 4). This means that after size reduction the filling up of the channel with the smallest flow-rate will be equal to 30% of the maximal possible.

4. If $Q_{mean} < 30\% U_{max}$, where $Q_{mean} = U_{max}/n$, and for $x_i < x_n$ condition Eq. (5) is not fulfilled, the hydraulic diameter is not changed until $x_i = x_n$ and the calculated height is increased with Δx as many times as these conditions occur.

Step 4 needs some explanation. In the region above C, the point of meeting of the two flows from adjacent feed points, the liquid flows predominantly in the channels along line AC ($x_i = x_n$) and the flow-rates there are much greater than the flow-rates from the rest of the points of a given horizontal row. By the calculation it was found that this condition could be approximately evaluated by the inequality $Q_{mean} < 30\% U_{max}$. So for the channels downstream of such a horizontal row if we reduce the groove cross-section according to step 3, the channel along AC takes in flow-rate much greater than U_{max} (with about 50%). If we decrease the cross-section so as the channel along AC to take in flow-rate equal to U_{max}, the degree of filling up of the channel with the minimal flow-rate is below 30%. Both possibilities result in going out of the range of validity of the equations used. That is why it is accepted that in this case the groove cross-section is unchanged and the results for the redistribution at that row of crossing points are not the actual. Since at the worst the liquid is not redistributed there at all, the calculated plate height should be increased with as many steps as the number of “non-distributing” rows, i.e. the plate height is determined with a small reserve.

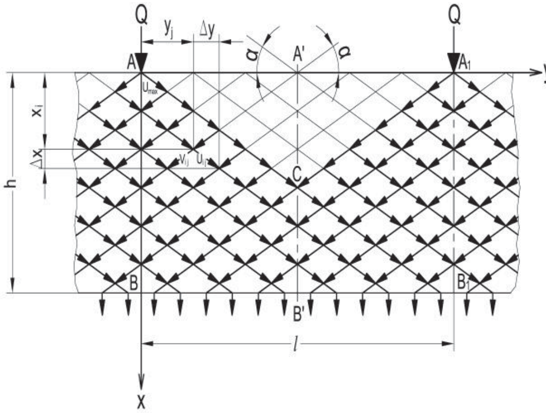

Fig. 3. Liquid spreading in the capillary grooves of a vertical plate. The arrows show the directions of the flows in the grooves. A, A_1 –Feed points; A'B' -Axis of symmetry.

5. Comparing the determined flow-rates from the crossing points of a horizontal row. If they differ more than the prescribed degree of uniformity the vertical coordinate, i.e current plate height, is increased,

$$x_i = x_{i-1} + \Delta x,$$

and step 2 is repeated for the next row of crossing points.

6. The calculation stops (at $i=m$, $x=x_m$) when the flow-rates in all the grooves at a certain horizontal row become practically equal with deviation from the mean value not more than a preliminary chosen percentage (e.g. 5%). The first and the end row of crossing points are located at a distance of $\Delta x/2$ from the plate ends. The design of the plate top and bottom edges ensures the best taking up of the liquid from the drip points above the plate and maximal number of drip points below the plate. According to Fig. 3 the plate height h is determined by

$$h = x_m + \Delta x. \quad (6)$$

Since the grooves distribute the liquid phase only in one vertical plane, the packing layer should comprise two rows of parallel plates, the plates of the second row perpendicular to the first. The packing layer height h_l is calculated by

$$h_l = 2h. \quad (7)$$

This is not valid for the liquid distributor in Fig. 1, where only one layer of redistribution packing is necessary because the plates with inclined grooves included in the distributor construction spread the liquid in planes perpendicular to the plates of the packing layer below.

3. PACKING LAYER HEIGHT

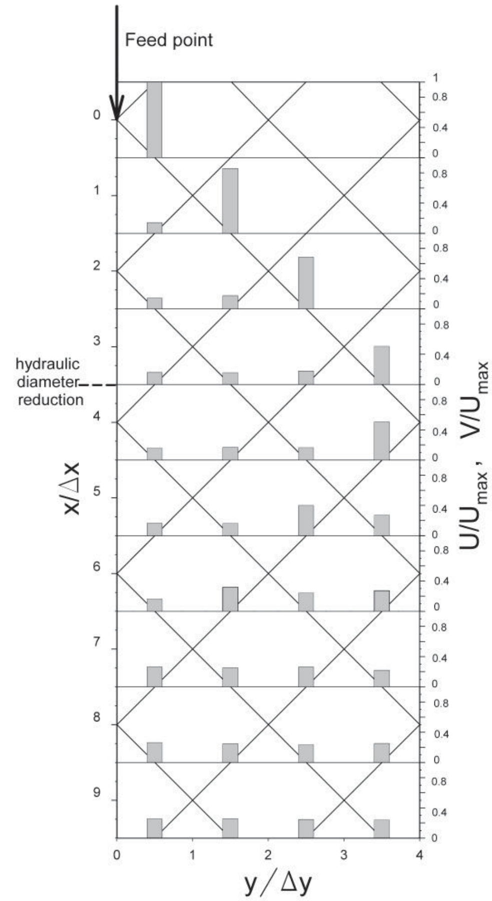

Fig. 4. Flow-rate distribution along a vertical plate with inclined grooves.

Fig. 4 presents the transition to equal flow-rate distribution along a vertical plate with capillary grooves, the bars representing the dimensionless flow-rates from a crossing point $U_{i,j}/U_{max}$ and $V_{i,j}/U_{max}$.

The calculation is performed with the following input data:

- angle of inclination of the grooves α=45º;
- steps between the crossing points Δy =14 mm;
- groove width and depth 2×2 mm;
- distance between the feed points l=112 mm;
- physico-chemical properties of liquid phase, water dynamic viscosity $\mu=1\text{x}10^{-3}$ Pa.s and density $\rho=1000$ kg/m^3, (at a temperature of 20ºC);
- flow-rate at the drip point $Q=2U_{max}=3.7\times10^{-6}$ m^3/s.

At the horizontal line $x_d/\Delta x=3.5$, Fig. 4, the hydraulic diameter has been reduced from d_h =2.67

mm (2×2 mm) to d_h' =2.23 mm (1.67×1.67 mm). The plate height is determined by the horizontal row at which the flow-rates become equal with the prescribed precision of 5% of the mean flow-rate Q_{mean}=0.462×10^{-6} m^3/s. As seen from Fig. 4, uniform flow-rates have been achieved at $x_m/\Delta x$=9, so the plate height, Eq. (6), is h=10Δx=140 mm. The packing layer height, Eq. (7), is

$$h_l=2h=280 \text{ mm}.$$

When using the new redistribution layer under the liquid phase distributor presented in Fig. 1 the layer height is

$$h_l=h=140 \text{ mm}$$

because the first layer of the redistribution packing is replaced by the distributor plates (2) with grooves presented in Fig. 1 as a part of the liquid phase distributor.

Since the new redistribution packing is intended for low liquid superficial velocity and because of the lack of such type of packings operating in similar regimes, it is compared with redistribution packings efficient at higher liquid superficial velocities, inclined Raschig rings [9], block packing of inclined plastic sheets [10] and inclined ceramic honeycomb packing [12].

Table 1 shows the calculated by means of Eq. (7) layer heights for different angles of groove inclination α = 45°, 30° and 15° versus the distance between the feed points, which is divisible by the horizontal distance between the grooves. The results show that the necessary plate height increases with increasing of the feed points distance. The observed exceptions for the plates α=45° and α=30° are due to the accepted precision of the calculations in respect to degree of uniformity of the liquid distribution and the circumstance that the height is multiple of the vertical distance between the grooves.

Table 1. Comparison of packing layer heights

Distance between drip points l, m	Packing layer height h_l, m					
	Plates with inclined grooves α=45°	Plates with inclined grooves α=30°	Plates with inclined grooves α=15°	Inclined ceramic Raschig rings, 49.1/41.2 mm, 16° D=2.85×10^{-3} m, [9]	Inclined plastic sheets, 22° D=1.4×10^{-3} m, [10]	Inclined ceramic honeycomb packing 27/50 mm, 24° D=2.67×10^{-3} m [12]
0.0560	0.1960	0.1132	0.0375	0.1067	0.2172	0.1139
0.0840	0.3920	0.1617	0.0450	0.2400	0.4886	0.2562
0.1120	0.2800	0.1455	0.0675	0.4267	0.8687	0.4555
0.1400	0.3360	0.1940	0.0600	0.6667	1.3573	0.7117
0.1680	0.3640	0.2263	0.1050	0.9601	1.9545	1.0248
0.1960	0.3920	0.1940	0.1425	1.3068	2.6603	1.3949

In Table 1 the height of the new packing is compared with the heights of an arranged packing of inclined ceramic Raschig rings with an outside diameter of 49.1 mm, an element height of 41.2 mm and an inclination angle of 16°, [9], a block packing of inclined plastic sheets with an inclination angle of 22°, [10] and an inclined ceramic honeycomb packing with an inscribed circle diameter of 27 mm, an element height of 49 mm and inclination angle of 24°, [12]. The previous investigations [9,10,12] show that just these angles are the optimal for the efficiency of the respective picking. The height ensuring flow uniformity with accuracy 5% of the mean superficial velocity is obtained by the following relation:

$$h = 0.09695\frac{l^2}{D} , \qquad (8)$$

proposed in [13] using the simple model of Kolev [14]. Here D, m, is radial liquid spreading coefficient.

Table 1 shows that the necessary height of the bed of plates with inclined grooves for a given distance between the drip points and liquid flow uniformity is much smaller than the heights of the packings from literature.

It is known, that the increasing of the liquid superficial velocity leads to increasing of the spreading coefficient [10] for the packing with inclined plates and does not affect this coefficient of the packings from [9 and 12]. That is why the value of D for inclined plates is taken for the region of low superficial velocities, where it does not depend on liquid superficial velocity.

4. PACKING RADIAL SPREADING COEFFICIENT

The radial spreading coefficient of the new packing is determined by Eq. (8) with the calculated heights in Table 1. Table 2 shows that *D* varies for different distances between drip points, i.e. different superficial velocities, because as expected the applied relation is not adequate. It is based on the assumption that the liquid spreading down a packing bed can be described in terms of rivulets of stable but randomly orientated path through the bed, which is a homogenous medium characterized merely by an empirical radial liquid spreading coefficient. Strictly speaking the random walk hypothesis accepted in [9–12] is inapplicable for arranged packings like these in [9,10,12], and yet it was used there for evaluation and comparison of their spreading ability with other packings. It is especially improper for the present new redistribution packing, where the path of the liquid rivulets is determined by the crossing grooves. That was the reason to develop a principally new method for calculation of the liquid spreading in the packing bed, the purpose of the present work.

Table 2. Radial spreading coefficients of packing of vertical plates with grooves

Distance between drip points l, m	Plates with inclined grooves α=45° D, m	Plates with inclined grooves α=30° D, m	Plates with inclined grooves α=15° D, m
0.0560	0.001551	0.002686	0.008108
0.0840	0.001745	0.004231	0.015202
0.1120	0.004343	0.008358	0.018017
0.1400	0.005655	0.009795	0.03167
0.1680	0.007517	0.012092	0.02606
0.1960	0.009501	0.019198	0.026136

5. CONCLUSION

A procedure is developed for calculation of the height of the redistribution bed of vertical plates with inclined capillary grooves at given degree of uniformity, distance between the drip points and required design. It uses equations proposed in [6, 7], obtained on the basis of an experimental study of the flow-rates in inclined crossing capillary grooves on vertical plates. On the basis of the investigation the new packing intended for low liquid superficial velocities is evaluated by comparison with other distributor packings showing that the necessary layer height of the proposed packing is much smaller than the heights of the packings from literature.

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ВИСОЧИНА НА ВЕРТИКАЛНИ ПЛАСТИНИ С НАКЛОНЕНИ КАПИЛЯРНИ КАНАЛИ ЗА ПРЕРАЗПРЕДЕЛИТЕЛЕН ПЪЛНЕЖЕН СЛОЙ В КОЛОНИ С ПЪЛНЕЖ

Д. Джонова-Атанасова*, Д. Колев, Н. Колев

Институт по инженерна химия, Българска академия на науките, ул.“Акад. Г. Бончев”, бл. 103, 1113 София, България

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(Резюме)

Равномерното разпределение на течната фаза по напречното сечение на колоната с пълнеж е основна предпоставка за ефективна работа на апарата. Сред съществуващите оросителни устройства най-добра равномерност се постига при тези от тях, които разпределят течността на струйки с равни дебити. Крайното преразпределение до равномерност по напречно сечение с размери от порядъка на пълнежен елемент се осъществява в самия пълнеж или в специално конструиран преразпределителен пълнежен слой. За тази цел е разработен и изследван нов пълнеж, особено подходящ за ниски плътности на оросяване. Той се състои от успоредни вертикални пластини с наклонени пресичащи се капилярни канали, щамповани върху тях. Разработена е компютърна програма за изчисляване на височината на преразпределителния слой при дадено разстояние между точките на оросяване на оросителното устройство. Изчислената височина осигурява, с избрана точност, равенство на дебитите на течната фаза, напускаща капилярните канали. Сравнението със съществуващите устройства показва, че при дадена степен на равномерност новият пълнеж се характеризира със значително по-малка височина.