HYDRODYNAMICS OF PLATE COLUMNS. VIII.*

THE DRY-PLATE PRESSURE DROP OF SIEVE-PLATE SEPARATING COLUMNS

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A qualitative and quantitative analysis is given of the relations proposed for the calculation of the dry-plate pressure drop of sieve-plate separating column on the basis of the experimental data. It has been found that for plates with the thickness-to-opening-diameter ratio greater than unity (the thick plates) the relation by Van Winkle suits best. A new relation has been obtained for the plates with the mentioned ratio smaller than unity from experimental data covering 78 plates. The average deviation of the relation is 5·4%.

The dry-plate pressure drop (the pressure drop with no inflow of liquid) of the separation columns is an important quantity for processing the operating pressure drop of the plates which in turn is important for the design of such equipment. The dry-plate pressure drop may be used either directly, if one assumes that individual resistances are additive, or may serve to obtain suitable relations for wet plates.

The plate represents an obstacle in the way of the gas passing through the column and the relations for the dry-plate pressure drop are therefore written in a manner analogous to the relations for local resistance to the flow of fluids

$$\Delta p_d = \zeta \frac{v^2 \varrho}{2\varphi^2} . \tag{1}$$

The resistance coefficient in Eq. (*1*) depends generally on the velocity and physical properties of the gas and the geometry parameters of the plate.

There are over 20 relations existing in the literature for the sieve-plate resistance coefficient. The values calculated from various relations are usually widely different. We have therefore conducted an impartial appraisal of the equations for the resistance coefficient by comparing the experimental values with the calculated ones. A set of experimental data measured on 110 plates available from the literature[1–15] has been obtained enabling a qualitative and quantitative evaluation to be made of the published relations. The investigated relations are summarized in Rylek's[1] and other more recent studies[10–12].

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The following qualitative conclusion regarding the effect of individual parameters were drawn from the analysis of the data:

Gas velocity. The effect of gas velocity is usually expressed in terms of the Reynolds number for plate openings. For thick plates the resistance coefficient decreases with increasing Reynolds number up to a value of about 3000 to 5000. Above this limit the resistance coefficient is no longer dependent on the Reynolds number (the region above the constancy limit). The dependence on the Reynolds number exhibits a steeper slope for plates with high value of the t/d ratio. No unambiguous effect has been detected for plates with $t/d < 1$. Various authors have found mutually contradicting trends on approximately identical plates. Thus we have concluded that in a part of the examined set of data characterized by $t/d < 1$ the effect of the Reynolds number on the resistance coefficient is insignificant.

Physical properties of the gas. From the experiments of Hunt and coworkers[7] it is clear that physical properties of gas do not affect the resistance coefficient. Besides air the gases used included methane, argon, carbon dioxide and freon 12. The density of gases ranged between 0·67 and 2·74 kg/m^3 and the viscosity between $1{\cdot}1 \,.\, 10^{-5}$ and $2.2 \,.\, 10^{-5}$ Ns/m^2. The experimental values of the resistance coefficient display no systematic deviation from the values obtained with air.

Geometry parameters of the plate. From physical standpoint it is convenient to form two groups of plates: The thick and the thin plates. On its passage through the plate the gas jet is separated from the wall of the opening on its leading edge. The jet first narrows to reach a minimum cross-section and only then expands back toward the walls of the opening. If the path of the gas through the plate is sufficiently long (thickness of the plate), the jet expands and fills the whole cross-section of the opening. The plates of sufficient thickness are referred to as the thick plates. Conversely, if the gas jet emerges from the opening with a cross-section smaller than that of the opening we speak of thin plates. The transition occurs at t/d between 0·8 to 1.

For thin plates the resistance coefficient increases with decreasing t/d ratio (established up to $t/d = 0{\cdot}1$). For thick plates above the constancy limit the coefficient is virtually independent of t/d up to 3 to 4 and further probably (lack of data) increases with increasing t/d.

The resistance coefficient generally increases with the d/P ratio. The dependence is steeper for thin than for thick plates. Some authors have used the relative free area of cross-section of the plate instead of d/P. Both quantities are mutually proportional, $\varphi = k(d/P)^2$, but the factor k depends on the arrangement of the openings and the ratio of the perforated to the total area of the plate.

Some other geometry factors must be mentioned too. Rylek[4] has studied two sieve plates of the same free cross-section and the same t/d ratio: one with a triangular, the other with a square pitch arrangement of the openings. The experimental values were for the plate with triangular arrangement by 6% lower on average. A similar conclusion has been made also by Arnold[14]. The experimental columns were of either oblong or circular cross-section and their area varied between 0·011 to 0·2 m^2. These factors had no effect on the resistance coefficient. The set of data gives no evidence of the effect of the working of the openings; all plates were made by drilling the openings in metal sheets and the opening edges were left unchamfered. The only exception is the plate made of PVC[6]. The resistance coefficient found on this plate was by 15 to 20% lower than on similar metal plate most probably due to more roundish edges of the openings drilled in PVC. Hunt[7] reports that plates which were not fixed during drilling exhibited the resistance coefficient by 18% lower than those properly mounted during drilling. The reason is probably the imperfect working of the leading edges of the openings.

The calculation of the resistance coefficients. A majority of the relations for the calculation of the resistance coefficient are correlations obtained on the basis of a relatively small number of experimental data covering a narrow range of plate geometry parameters. Consequently, only three equations with a broader validity will be examined in the following which conform best with the findings just briefly outlined.

McAllister and coworkers[16] assumed that the total coefficient of resistance is a sum of partial coefficients corresponding to contraction, $0{\cdot}4\ (1{\cdot}25 - \varphi)$, expansion $(1 - \varphi)^2$ and friction $4f(t/d)$. Since the expressions for these coefficients were derived for a single opening, the authors modified the equation by introducing another coefficient, k_1, accounting for mutual interference of parallel streams of gas, irregularity of the gradient in the openings and the Couette correction

$$\zeta = k_1 \,.\, [0{\cdot}4(1{\cdot}25 - \varphi) + (1 - \varphi)^2 + 4f(t/d)]\,. \tag{2}$$

The coefficient k_1 was evaluated from available experimental data and its dependence on t/d correlated graphically.

The approach of the authors has certain drawbacks. The use of the Fanning's friction factor is not appropriate because the flow within the openings is strongly affected by the entrance effects. By introducing k_1 the authors back up from the original assumption of additivity of pressure losses. There is no basis for assuming that the pressure losses by contraction, expansion and friction are affected by the t/d ratio in the same way. For thick plates the average deviation of the calculated and experimental values is 16%, for thin plates 13%.

Kolodzie, Smith and Van Winkle[17,18] used the classical orifice equation and assumed that its coefficient for sieve-plate openings may be correlated by analogous dimensionless groups as that for the orifice. They found that the orifice coefficient depends on the Reynolds number within the openings, the free area and the geometry simplexes t/d and P/d. By processing an extensive set of experimental data they obtained

$$\zeta = \frac{(1 - \varphi^2)\,(P/d)^{0{\cdot}2}}{k_2^2}\,, \tag{3}$$

where the dependence of k_2 on the t/d ratio and the Reynolds number was given in a graphical form.

Eq. (3) satisfies all qualitative requirements for thick plates and the average deviation found on our set of data equalled 8%. For thin plates the same equation yields a complicated dependence of the resistance coefficient on the Reynolds number, the fact which was not confirmed by the experimental data. When using the value from above the constancy limit for the coefficient k_2 the average deviation for thin plates amounts to 11%. As a disadvantage of Eq. (3) appears also the graphical form of the correlation of k_2.

Keule and Zelfel[10] assumed that the resistance coefficient for thick plates may be expressed as a sum of partial resistance coefficients by contraction $(1/\alpha - 1)^2$ and expansion $(1 - \varphi^2)$, both equal to those for a single opening, plus friction. The friction coefficient was determined as a difference between the experimental value of the resistance coefficient and partial coefficients of resistance due to contraction and expansion and correlated with the dimensionless group $K = \mathrm{Re}(d/t)\,(t/P)^{0{\cdot}7}\, n^{0{\cdot}25}$. The authors obtained the following relations:

$$\zeta = (1/\alpha - 1)^2 + \frac{2000}{K^{1{\cdot}2}} + (1 - \varphi)^2 \quad \text{for} \quad K < 2000,$$

$$\zeta = (1/\alpha) - 1)^2 + \frac{50}{K^{0{\cdot}715}} + (1 - \varphi)^2 \quad \text{for} \quad K > 2000. \tag{4}$$

The validity of the correlation was confined to t/d ranging between 1 and 4.

A weak point is the apriori use of the resistance coefficients due to contraction and expansion valid for single openings. A more serious drawback from practical viewpoint though is that the number of the openings, which is an extensive quantity depending on the area of column cross-section, appears in the definition of the dimensionless quantity K (for a circular column for instance we have $h = \varphi D^2/d^2$). This can be hardly justified because the authors experimented on a single column 180 mm in diameter. According to our findings, the resistance coefficient is independent of the size of experimental equipment. Eq. (4) describes well the effect of other quantities and the average deviation was 6·6%. The favourable agreement comes from the fact that almost half of the data for thick plates was taken from the experiments of the authors of Eq. (4). The objection raised against the number of openings appearing in the definition of K could not become manifest because a majority of measurements was taken in columns of a similar cross-section as that used by the authors of the criticised paper.

From the published relation it appears that probably the best is Eq. (3). Its accuracy suffices for the calculation of the thick plates pressure drop but the accuracy is unsatisfactory for thin plates. We have therefore examined the problem of pressure drop of thin plates in more detail.

EXPERIMENTAL

14 thin sieve plates without downcomers were investigated experimentally in a column 288 mm in diameter. The dry-plate pressure drop was measured as a difference between pressures above and below the plate. The pressure probes were located 550 mm above and 150 mm below the plate. The accuracy of measurement was within 5 N/m^2.

RESULTS

Our experimental results only confirmed the above mentioned qualitative findings and extended the set of data intended for formulating the correlation. In the search of a suitable relation we started similarly as Van Winkle and coworkers[17] from the theoretical assumptions that the resistance coefficient could generally depend on the Reynolds number of the opening and the simplexes (t/d) and (d/P).

From the analysis of the dependence of the pressure drop on gas velocity it follows that for thin plates the effect of the Reynolds number on the resistance coefficient is insignificant. For mathematical processing the experimental values of the resistance coefficient found on different plates at various gas velocities were averaged. The results measured at low gas velocities were not taken into the average owing to the lower relative accuracy of the pressure drop measurement. Thus by experimental values we mean the averages obtained as has been just described. In order to diminish the number of variables necessary for the description, the (d/P) ratio was replaced by the relative free area φ. By processing the set of data representing 78 plates we have obtained

$$\zeta = A \frac{(1 - \varphi^2)}{\varphi^{0 \cdot 2}(t/d)^{0 \cdot 2}}, \tag{5}$$

where $A = 0{\cdot}94$ or 1 for a triangular and a square pitch arrangement of openings respectively. The published experimental data come from 11 sources[2-4,8-15] and cover 64 plate geometries. A comparison of the experimental and calculated values yields the average deviation equal to 5·4%; more than 85% of data deviates by less than 10%.

Eq. (5) can be used to calculate the resistance coefficient of sieve plates ranging in t/d between 0·1 and 0·8 and the relative free area of cross-section between 0·015 and 0·2. A small extrapolation beyond these limits is permissible. An advantage of Eq. (5) is the analytical character of the dependence of the resistance coefficient on the geometry parameters of the sieve plates. Moreover, this relation is less complex and on our set of data substantially more accurate than the best of the correlations published to date.

On substituting from Eq. (5) into (1) one gets

$$\Delta p_\mathrm{d} = A\varphi^{-0\cdot2}(d/t)^{0\cdot2}\left[\frac{\varrho v^2}{2}\left(\frac{1}{\varphi^2} - 1\right)\right]. \qquad (6a)$$

The expression in the bracketts gives the difference of the kinetic energy of the gas within the plate openings and that in the empty cross-section of the column. Defining now the resistance coefficient as a factor of this energy difference we have

$$\Delta p_\mathrm{d} = \zeta' \frac{\varrho v^2}{2}\left(\frac{1}{\varphi^2} - 1\right), \qquad (6b)$$

where

$$\zeta' = A\varphi^{-0\cdot2}(d/t)^{0\cdot2}. \qquad (7)$$

Expressing $A \, . \, \varphi^{-0\cdot2}$ in Eq. (7) in terms of the pitch of the rows of the openings P', and the opening diameter we obtain after some manipulation for the square pitch

$$\zeta' = 1{\cdot}049\left(\frac{P'^2}{td}\right)^{0\cdot2} \qquad (8a)$$

and for the triangular pitch

$$\zeta' = 1{\cdot}015\left(\frac{P'^2}{td}\right)^{0\cdot2}. \qquad (8b)$$

The difference in the values of the coefficients in Eqs (8a) and (8b) is statistically insignificant and thus we may write for both cases with sufficient accuracy

$$\zeta' = 1{\cdot}03 \left(\frac{P'^2}{td}\right)^{0{\cdot}2} . \tag{8c}$$

From Eq. (*8c*) it therefore follows that the resistance coefficient defined by Eq. (*6b*) depends on the (P'/t) and (P'/d) simplexes and the type of the correlation is for both arrangements the same.

All relations published to date, including Eq. (*5*), were formulated on the basis of the data measured on drilled plates with sharp leading edge of the openings. It may be expected that the resistance coefficient of the plates manufactured industrially by a technique producing openings with rounded leading edge (*e.g.* by punching) will generally be smaller than that computed from the relations recommended in this paper.

LIST OF SYMBOLS

A	coefficient in Eq. (*5*)
D	column diameter
d	opening diameter
f	Fanning's friction factor
K	dimensionless group defined in text
k, k_1, k_2	coefficients
P, P'	opening pitch, resp. pitch of the rows of the openings ($P' = P.(\sqrt{3}/2)$ for triangular and $P' = P$ for square arrangement of openings).
Δp_d	dry-plate pressure drop
Re	Reynolds number in the opening
t	plate thickness
v	gas velocity in the column
α	coefficient of contraction
δ	relative deviation of the experimental and the computed value
ζ, ζ'	resistance coefficient defined by Eq. (*1*) or (*6b*)
φ	relative free area of cross-section
ϱ	gas density

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