THE PRESSURE DROP OF SIEVE-PLATE COLUMNS*

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On the basis of the analysis of experimental data a relation has been obtained for the difference of the total pressure drop and liquid hold-up as a function of the flow rates of phases, the geometry parameters of the plates and the properties of the phases. The relation pertains also to sieve plates with downcomers. In both cases the validity is restricted to plates wih the plate thickness to opening diameter ratio smaller than unity.

Under the counter-current flow of liquid and gas through plates without downcomers both phases are forced to pass through the same openings of the plate in a random sequence. On the plate there exists simultaneously a certain number of bridged openings by-passed by both phases. Passing gas occupies only a part of the plate free area, $\varphi\Theta$, where $\Theta \in (0; 1)$. Similar situation exists on plates with downcomers but the liquid may either completely by-pass the plate through the downcomers, or may pass through the plate only partially (weeping).

The analysis of the relation between the total pressure drop and liquid hold-up on the plate was based on the force and momentum balance. The boundaries of the check volumes for the balance are formed (Fig. 1) by three horizontal planes: *1* and *2* for the first and *2* and *3* for the second of the volumes. The plane *1* is placed sufficiently below the plate for the gas stream to be free of the contraction effect on entering the plate openings. The plane *2* is identical with the upper surface of the perforated plate. The plane *3* is located again well above the gas liquid mixture where the flow of the gas is already uniform. The general force and momentum balance may be simplified with the following acceptable assumptions: *1*) Steady state operation; *2*) Equal column diameter in all check cross sections; *3*) No interfacial transport of mass; *4*) Negligible friction losses on the column wall; *5*) Negligible change of momentum of the liquid on passing through the system; *6*) Uniform pressure over the check cross sections *1* and *3*. The pressure in the cross section *2* is not uniform but may be replaced by some average value $\bar{p}_2$.

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The balance equations related to a unit area of the plate are:

For the check volume between the planes *1* and *2*

$$p_1 + v(v\varrho_g) = \bar{p}_2 + (v/\varphi\Theta)(v\varrho_g) + F\,, \tag{1}$$

F is the force exerted by the wet plate against the stream of gas. In view of the assumption 4 F is the only external force acting on the system.

For the check volume between the planes *2* and *3* then

$$\bar{p}_2 + (v/\varphi\Theta)(v\varrho_g) = p_3 + v(v\varrho_g) + h\varrho_l\boldsymbol{g}\,, \tag{2}$$

The term $h\varrho_l\boldsymbol{g}$ represents the force due to the presence of liquid hold-up. From Eqs (*1*) and (*2*) one can obtain a relation between the total pressure drop and liquid hold-up as $\Delta p = p_1 - p_3 = h\varrho_l\boldsymbol{g} + F$. The force F, in accord with its physical meaning, is referred to as the resistance of the plate proper, Δp_w.

$$\Delta p = h\varrho_l\boldsymbol{g} + \Delta p_w\,. \tag{3}$$

In search for an expression for the resistance of the plate proper the concept was employed of an identical dry plate with a part of the openings blinded. The plate is blinded in a manner keeping the same number of equally spaced openings free for the flow of the gas as that on the wett plate. Analogous balance equations as those in Eq. (*1*) and (*2*) were written for the hypothetical dry plate. The symbols are distinguished by primes.

For the system bound by the planes *1* and *2* one obtains

$$p'_1 + v'(v'\varrho_g) = p'_2 + (v'/\varphi\Theta)(v'\varrho_g) + F'\,. \tag{4}$$

Without any loss of generality one can put $p'_1 = p_1$ and $v' = v$. It may be assumed that the contraction of the gas stream entering the openings of the hypothetical dry plate takes place in the same manner as it would on that with the gas–liquid mixture. In such case the force F' exerted by the dry plate against the stream of gas equals the force F exerted by the wet plate. From Eqs (*1*) and (*4*) it then follows that also $p'_2 = p_2$ and the two equations become identical. The balance for the check volume between the planes *2* and *3* takes the form

$$\bar{p}_2 + (v/\varphi\Theta)(v\varrho_g) = p'_3 + v(v\varrho_g)\,. \tag{5}$$

From Eqs (*4*) and (*5*) after the above considerations one obtains

$$\Delta p'_d = p_1 - p'_3 = F' = F = \Delta p_w\,. \tag{6}$$

The resistance of the wet plate proper thus equals the resistance of the hypothetical dry plate of the free area $\varphi\Theta$ and identical spacing and configuration of the openings opened for the gas as that on the wet plate.

From Eqs (2) and (5) it follows that the loss due to expansion is not affected by the presence of the gas–liquid mixture either and it is thus identical for both the wet and the hypothetical dry plate. Similar conclusions have been arrived at experimentally by Steiner[1].

For the resistance of a thin plate the following relation is available[2]

$$\Delta p_d = \zeta_d \frac{v^2 \varrho_g}{2\varphi^2} = A \cdot \frac{(1 - \varphi^2)}{\varphi^{0.2}(t/d)^{0.2}} \frac{v^2 \varrho_g}{2\varrho^2}, \tag{7}$$

where A equals 0·94 and 1·0 for the triangular and the square pitch arrangement respectively. Eq. (7) suits well for estimating the pressure loss of sieve plates with t/d ranging between 0·1 and 0·8, the free area between 0·015 and 0·2 and the opening diameter between 1 and 15 mm. Eq. (7) can be rearranged to give a form convenient for the calculation of the resistance of the hypothetical plate by substituting the free area φ by $\varphi\Theta$ and introducing a coefficient k_1 to account for increased resistance of the plate due to possible non-uniform configuration of the openings available for gas flow.

$$\Delta p_w = \Delta p'_d = k_1 A \frac{(1 - \varphi^2 \Theta^2)}{\varphi^{0.2} \Theta^{0.2} (t/d)^{0.2}} \frac{v^2 \varrho_g}{2\varphi^2 \Theta^2}. \tag{8}$$

Since the term $(1 - \varphi^2\Theta^2)/(1 - \varphi^2)$ is usually close to unity Eq. (8) may be written in a simpler form as

$$\Delta p_w = k_1 \xi_d (v^2 \varrho_g / 2\varphi^2 \Theta^{2.2}). \tag{8a}$$

From physical standpoint the quantity Θ represents the number of the openings available for gas flow as a fraction of the total number of the openings on the plate. Its magnitude is given by the dynamic equilibrium of the forces that tend to open or bridge the openings. The forces tending to bridge the openings are the surface tension forces acting within the openings which are directly proportional to the surface tension of the liquid and indirectly proportional to the opening diameter $(k_2\sigma/d)$. The force that breaks the paths open for the gas is the pressure difference between a point below and just above the plate $(p_1 - p_2)$. The combined effect of the two types of forces may be approximated by

$$\Theta = 1 - (k_2 \sigma / d)/(p_1 - \bar{p}_2). \tag{9}$$

On combining Eq. (1) and (8a) one obtains

$$p_1 - \bar{p}_2 = k_1 \xi_d \frac{v^2 \varrho_g}{2\varphi^2 \Theta^{2.2}} + v^2 \varrho_g \left(\frac{1}{\varphi\Theta} - 1 \right). \tag{10}$$

On substituting from Eq. (*10*) into (*9*) and after some arrangement a relation is obtained expressing implicitly the dependence of Θ on the superficial gas velocity, physical properties of the phases and plate geometry

$$v^2\varrho_g = \frac{k_2\sigma/d}{(1-\Theta)\left[(k_1\sigma_d/2\varphi^2\Theta^{2\cdot2}) + (1/\varphi\theta) - 1\right]}\,. \qquad (11)$$

Eq. (*11*) contains the coefficients k_1 and k_2 which must be evaluated from experimental data. Their physical meaning have been given in the preceeding text.

EXPERIMENTAL

The experiments were carried out on a one-plate hydraulic model 288 mm in inner diameter using the water–air system. The total pressure drop was detected by pressure taps located 150 mm below and 550 mm above the plate. The accuracy of the pressure drop measurements was 2%. Liquid hold-up was measured by stopping the column operation and weighing. The results were corrected on the dead hold-up determined experimentally in advance. The reproducibility of the hold-up measured was within ±2·5%. A detailed description of experimental set-up as well as the experimental technique of measuring the hold-up has been published earlier[3]. A total of 14 plates were studied, all of which being 2 mm thick. The variable parameters of the plates were the

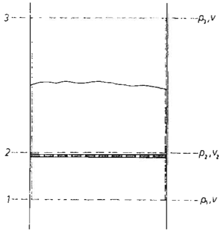

FIG. 1

Sketch of Check Volumes

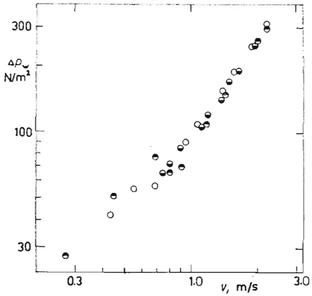

FIG. 2

The Resistance of the Plate Proper as a Function of Gas Velocity with Liquid Mass Velocity as a Parameter

Plate geometry: *d* 10 mm, φ 0·1494, *t* 2 mm, inner column diameter 288 mm. Mass velocity of liquid (kg/m² s): ◒ 0·2; ○ 1·2; ◓ 4·0.

opening diameter (2·5—10 mm) and plate free area (5—20%). The geometry parameters of the plates examined were summarized in the above cited paper[3].

RESULTS

The value of the resistance of the plate proper was determined as the difference of the total pressure drop and the hold-up of liquid. For gas velocities above the loading point the plot of the total pressure drop *versus* gas velocity displays a smooth course without abrupt changes. It was further established that within the experimental error the resistance of the plate proper depends on the flow rate of the gas only and not the liquid (Fig. 2). Hence the resistance of the plate proper is also independent of liquid hold-up.

The experimental course of Δp_w as a function of the velocity factor $v\varrho_g^{1/2}$ provides the estimate of the coefficients k_1 and k_2 for individual plates. The evaluation was carried out by trial and error. The search was for a pair of k_1 and k_2 providing the best possible fit of the theoretical Δp_w *versus* $v\varrho_g^{1/2}$ function calculated from Eqs (*11*) and (*8a*) with the experimental one. It turned out that the coefficients k_1 and k_2 may be regarded as constants for all 14 plates examined regardless of the geometry. The average values found were 1·10 and 2·35 for k_1 and k_2, respectively.

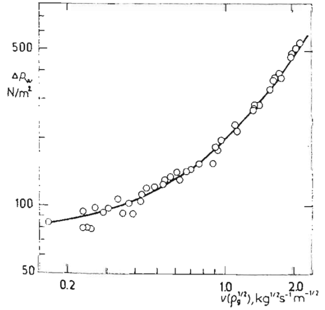

FIG. 3

Experimental and Computed Values of the Resistance of the Plate Proper *versus* the Velocity Factor for the Water–Air System

Plate geometry: *d* 2·5 mm; *φ* 0·0978, *t* 2mm, inner column diameter 288 mm.

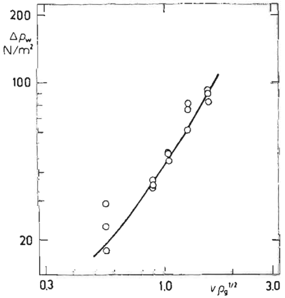

FIG. 4

Experimental and Computed Values of the Resistance of the Plate Proper *versus* the Velocity Factor for the Ethanol–Air System

Plate geometry: *d* 12 mm; *φ* 0·1755, *t* 2 mm, inner column diameter 120 mm.

The resistance of the plate proper can be computed from Eqs (*8a*) and (*11*). The geometry parameters delimiting the range of applicability are given by the range of validity of Eq. (*7*). The equation applies to all regimes of plate operation excepting those below the loading point.

The agreement of the experimental data with the calculated values is very good. Fig. 3 shows a typical$_s$ plot of Δp_w *versus* the velocity factor $v\varrho_g^{1/2}$ in comparison with the calculated curve. The outlined method agrees qualitatively with the published experimental observation of the effect of surface tension[4] but there have been no data thus far published in the literature enabling this effect to be verified quantitatively. Several experiments designed to test this effect were carried out using the ethanol--water system in a column 120 mm in inner diameter. The experimental Δp_w comport fairly well with the computed course as may be apparent from Fig. 4.

Since liquid flow rate within the investigated range has no effect on Θ the method should also pertain to thin plates with downcomers. Sufficiently accurate data on liquid hold-up could not be found in the literature. The data on pressure drop across the gas–liquid mixture measured on a single radius cannot be used since they are not representative of the whole plate[3]. The data in acceptable form are those of Brambilla and coworkers[5] (measured in a 186 × 411 mm column) and Brown[6] (600 × 600 mm column) both with the water–air system. In both cases the authors measured the pressure drop across the gas–liquid mixture on several radii of the plate enabling the averages $p_1 - \bar{p}_2$ to be determined. These experimental data were in a good agreement with the theoretical curve computed this time from Eq. (*10*) instead of (*8a*).

LIST OF SYMBOLS

A	empirical coefficient
d	opening diameter
F	force per unit area of plate exercised by plate against gas flow
g	acceleration due to gravity
h	clear liquid height on plate
k_1, k_2	empirical coefficients
p	pressure
$\overline{p_2}$	average pressure in the upper level of plate
t	plate thickness
v	superficial gas velocity
Δp	total pressure drop of wet plate
Δp_w	resistance of wet plate proper
Δp_d	dry plate pressure drop
φ	relative free area of plate
Θ	number of plate openings opened for gas as a fraction of total
ζ_d	dry plate resistance coefficient
ϱ_g	density of gas
ϱ_l	density of liquid

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