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HYDRODYNAMICS OF A NEW TYPE OF STRUCTURED PACKING

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ABSTRACT. New bench scale measurements of the gas-side pressure drop have been carried out using columns equipped with two different packings: conventional Raschig rings, and a structured packing of Mellapak 750 Y type. The pressure drop per unit height, at the same loading, was about twenty folds smaller in the structured packing. The data have been further correlated on the basis of a new fluid-dynamics model, valid for any type of packing. It has been found that the packing constant C_p is not dependent only on the texture of the packing. It linearly increases with the liquid load.

INTRODUCTION

The main applications for packed columns are the separation processes such as absorption, desorption, rectification, and extraction. In the last few years these processes were not still confined to petroleum refineries, chemical and allied industries but they were adopted on wider scale in ecological engineering for purifying off –gas streams and for water treatment. Consequently, the demand for the necessary equipment, including packing, is growing.

A major criterion in selecting the packing for absorption process, in which the gas is forced through the column by a compressor, is the *pressure drop* in the bed. It largely governs the compressor rating and the final operating cost of the process. The pressure drop per unit height of bed depends on the gas and liquid load, as well as on the hydrodynamic characteristics of the packing.

Packing stacked in a regular pattern, also called *structured packing*, makes it possible to decrease the pressure drop per theoretical stage and is therefore most suitable for minimizing energy consumption in separations that necessitate many stages. It also permits the lowest possible temperature at the column bottom in the separation of heat – sensitive mixtures. Maldistribution, which is often observed in conventional beds and which greatly impairs the efficiency can be largely avoided with this new types of column interiors. A factor that restricts their widespread acceptance is the capital investment cost. They are considered uneconomical at pressure drops higher than 10 mm WG per theoretical stage [1]. New and cheaper, yet more effective structured packings had to be developed. Mellapak 750 Y, recently

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introduced on the market by Sulzer, is one of the most promising structured packings.

The optimum design of absorption columns equipped with such new packings requires sound mathematical models derived from comprehensive physical relationships between the packing performance, the fluid dynamics, and the properties of the system to be separated. Until now, the approach commonly followed was to use semiempirical equations with uncertain limits of application [1]. The specific models derived to predict the pressure drop in particular geometric packing [2-5] don't allow a comparison of different packings performance. Bravo et al. [6] have proposed a more comprehensive model but, because of the large number of adjustable parameters, its application in ranges outside the tested region can lead to sizable errors [1].

A more general model, including a single packing constant (C_p) is derived and tested in this work. The model, based on the Billet's fluid-dynamics assumptions [7], describes the resistance to flow in terms of column load and liquid holdup, the physical properties of the liquid -gas system, and the packing characteristics. On the basis of experimental data, the constant C_p is identified for the Mellapak 750Y type of structured packing.

EXPERIMENTAL

The flow chart of the bench-scale plant used for the absorption rate and pressure drop measurements is reproduced in the Figure 1.

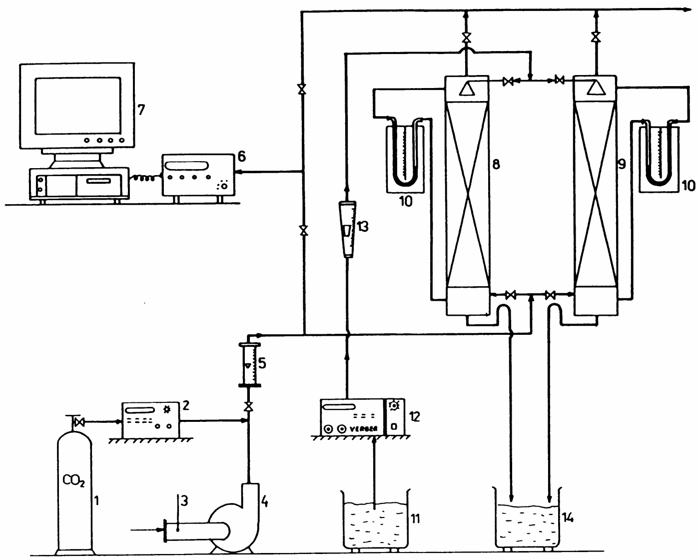
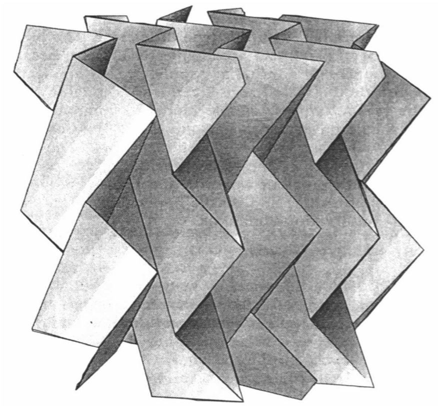


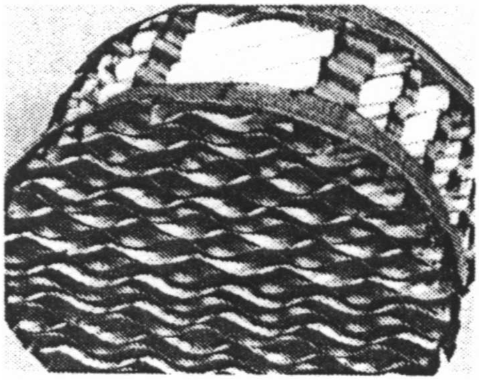
Figure 1. The experimental bench-scale plant

1- carbon dioxide cylinder, 2- carbon dioxide mass-flow meter, 3-air temperature controller, 4- air blower, 5- rotameter, 6- gas analyzer, 7- IBM compatible personal computer, 8/9- absorption columns, 10- manometer (mm WG), 11/14- solution tanks, 12- liquid pump, 13- liquid rotameter.

The first absorption column was equipped with a conventional bed of random packing: Raschig rings made of glass, with a nominal diameter of 10 mm. The second column contained an almost equal volume of Mellapak 750 Y structured packing from Sulzer SA. Geometrically, this was made of corrugated sheets arranged in parallel, successive layers having an opposite angle of corrugation as shown in Figure 2.a. The flow channels resulting from this arrangement are inclined at an angle of 45 degrees to the horizontal. The particular form of this packing makes it possible to obtain a specific surface as high as 750 m^2/m^3 in the case of Mellapak 750Y type. The picture of module of this packing is presented in Figure 2.b. The main geometric characteristics of the two absorption columns as well as the physical properties of the system used for pressure drop experiments are listed in the Table 1.



a.



b.

Figure 2. Structured packing of Mellapak 750 Y type.
a- corrugated sheets, b- element of structured packing.

Table 1.

Data on the investigated systems

Packing	Raschig rings	Mellapak 750Y
Column diameter (m)	0.100	0.100
Packing height (m)	0.550	0.518
Packing volume ($10^3 m^3$)	4.3175	4.0663
Nominal packing size (mm)	10 x 8 x 10	-
Equivalent diameter (mm)	2.105	0.400
Void fraction of the bed	0.800	0.950
Geometric surface area (m^2/m^3)	570	750

Liquid density (kg/m^3)	998.2
Liquid viscosity (Pa.s)	1.01×10^{-3}
Gas density (kg/m^3)	1.182
Gas viscosity (Pa . s)	17.84×10^{-6}
Temperature (K)	298
Pressure (bar)	1.00
Liquid flow rates (L/h)	0,30,40,50,60,70,80,100,150,200,250,300
Gas flow rates (m^3/h)	0,1,2,3,4,5,6,7,8,9,10,15,20,25

Corresponding to the thirteen gas flow rates and 12 liquid loads, a number of 312 ΔP - v_G pairs have been measured for the two packings.

RESULTS AND DISCUSSION

The directly measured pressure drops (mm WG) at different gas flow rates for some values of the liquid load are presented in the Table 2 (Raschig rings) and Table 3 (Mellapak 750 Y).

Table 2.

Pressure drop (mm WG) in the experimental column packed with Raschig rings.

V_G, m^3/h	V_L (10^3 m^3/h)						
	0	30	50	100	150	200	250
0	0	0	0	0	0	0	0
1	1	4	5	12	14	17	20
2	2	10	13	20	25	26	36
3	3	21	25	30	33	34	42
4	4	27	30	35	38	39	50
5	5	29	34	40	44	47	65
6	7	33	38	46	52	57	78
7	8	37	41	53	62	69	87
8	11	40	48	60	74	85	110
9	14	50	58	72	107	130	180
10	17	55	62	78	160	185	250
15	30	122	250	390	510	610	900
20	47	350	-	-	-	-	-
25	70	-	-	-	-	--	-

Table 3.

Pressure drop (mm WG) in the experimental column equipped with structured packing Mellapak 750 Y

V_G, m^3/h	V_L (10^3 m^3/h)						
	0	50	100	150	200	250	300
0	0	0	0	0	0	0	0
1	0	1	2	2	2	3	4
2	0	1	2	2	2	3	5
3	1	2	2	2	3	4	6
4	1	2	3	3	4	6	8
5	1	2	3	3	4	8	10
6	1	2	5	7	8	15	16
7	2	3	5	8	11	18	20
8	2	4	6	8	13	20	24
9	3	5	7	9	17	23	29
10	3	6	8	10	21	26	33
15	4	9	12	18	32	45	60
20	8	13	32	36	42	60	86
25	15	22	53	62	75	88	122

The two absorption columns had the same diameter and almost the same height of packing (see Table1). Therefore, this row experimental data allow a primary comparison of the pressure drops in the two packings at identical loads. At V_L = 0.250 m^3/h and V_G = 15 m^3/h , for instance, the ratio ($\Delta P_{Raschig} / \Delta P_{Mellapak}$) is as high as 900/45 =20. The advantage of Mellapak is obvious. A more rigorous comparison can be done by representing the pressure drop per unit height of bed (mbar/m) versus the capacity factor F_v, for constant liquid load, in the two packings (Figure 3).

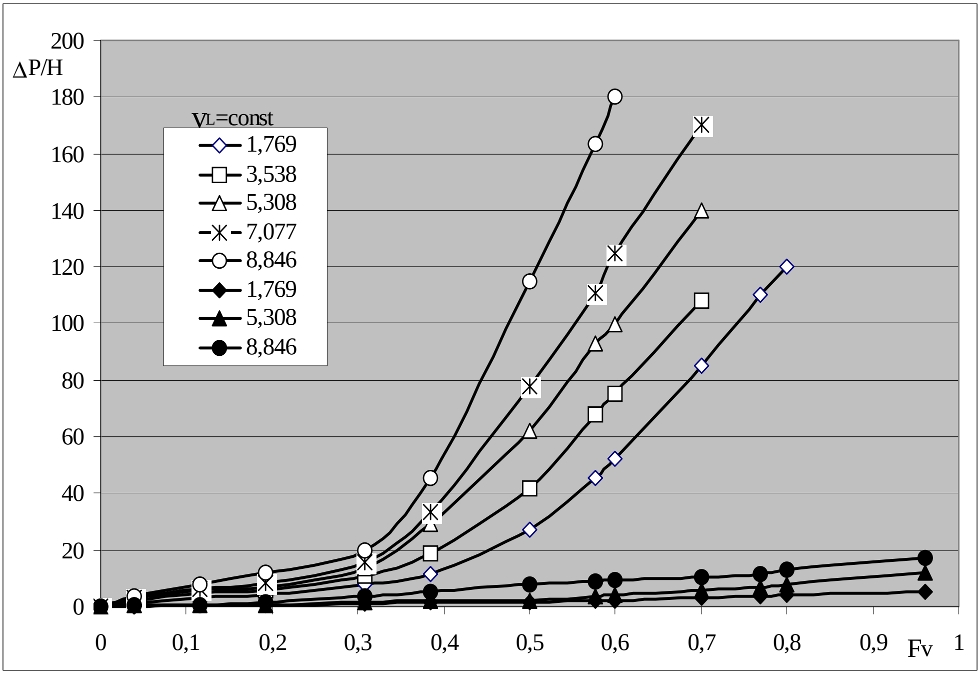


Figure 3. Pressure drop per unit height of bed (mbar/m) versus gas capacity factor at given liquid loads for the two packings (white figures: Raschig, black figures: Mellapak).

Mathematical modeling

The equations found in the literature for the prediction of gas –side pressure drop in packed columns are usually empirical or semiempirical. Moreover, they have been derived from studies on traditional packing and can not be applied unreservedly to modern, structured types. The aim of this paragraph is to present theoretical equation allowing the prediction of pressure drop for both conventional and modern types of packing. It is based on the fluid-dynamics model described by Billet [7]. The main assumption of the model is that the effective void fraction of the bed is equivalent to a number of vertical flow channels in which the liquid flows in the form of the film of thickness x_0 at an average velocity u_G. the gravity and shear forces are held in equilibrium within the film by the frictional forces that act in the gas at the surface of the film:

$$\mu_L\left(\frac{du_L}{dx}\right)_{x=x_0} = k\mu_L - \rho_l g x_0 = \zeta\rho_G \frac{{u_G}^2}{2} \qquad (1)$$

The pressure drop per unit height of the bed with effective area a_e and effective void fraction $\varepsilon_e = \varepsilon - \varepsilon_L$ is:

$$\frac{\Delta P}{H} = \left(\frac{a_e}{\varepsilon - \varepsilon_L}\right)\zeta\rho_G \frac{{u_G}^2}{2} \qquad (2)$$

The effective area a_e is the sum of the unwetted area (a_u) and the area of the liquid surface (a_w) in the flow channels. Taking into account the definition of the gas load:

$$v_G = (\varepsilon - \varepsilon_L)u_G \qquad (3)$$

and the wall factor f_w:

$$f_w = 1 + \frac{4}{aD} \qquad (4)$$

the equation of the pressure drop becomes:

$$\frac{\Delta P}{H} = \zeta_L \frac{a}{(\varepsilon - \varepsilon_L)^3}\left(\frac{a}{2} + \frac{2}{D}\right)\rho_G {v_G}^2 \qquad (5)$$

were:

$$\zeta_L = \zeta\left(\frac{a_u + a_w}{a}\right) \qquad (6)$$

In the extreme case, when $\varepsilon_L = 0$, i.e. $a_w=0$, the equation of pressure drop through an unwetted bed of packing is derived from (5):

$$\frac{\Delta P_0}{H} = \zeta_0 \frac{a}{\varepsilon^3}\left(\frac{a}{2} + \frac{2}{D}\right)\rho_G {v_G}^2 \qquad (5')$$

where ζ_0 is the resistance factor for the dry bed. From (5) and (5') the extend to which the pressure drop in the gas stream within the wetted bed exceeds that within the dry bed is derived:

$$\frac{\Delta P}{\Delta P_0} = \frac{\zeta_L}{\zeta_0}\left(\frac{\varepsilon}{\varepsilon - \varepsilon_L}\right)^3 \tag{7}$$

The equation (7) states that the higher the liquid load, the higher the pressure drop. This expected conclusion is validated by our experimental results in Tables 2 and 3.

The resistance factor ζ_0 can be determined with the following equation taken from the literature [9]:

$$\zeta_0 = C_p\left(\frac{64}{\mathrm{Re}_G} + \frac{1.8}{\mathrm{Re}_G{}^{0.08}}\right) \tag{8}$$

where:

$$\mathrm{Re}_G = \left(\frac{v_G d_p \rho_G}{(1-\varepsilon)\mu_G}\right) f_w \tag{9}$$

$$d_p = \frac{6(1-\varepsilon)}{a} \tag{10}$$

The constant C_p characterizes the geometry and the surface of the unwetted packing and is therefore specific for any type of packing. It must be determined experimentally.

Using the equation (7) the resistance factor in the gas-liquid flow becomes:

$$\zeta_L = C_p F_w\left(\frac{64}{\mathrm{Re}} + \frac{1.8}{\mathrm{Re}_G{}^{0.08}}\right)\left(\frac{\varepsilon - \varepsilon_L}{\varepsilon}\right)^{1.5} \tag{11}$$

The wetting factor F_w is a function of Re_L and the liquid holdup [8]:

$$F_w = \left(\frac{\varepsilon_L}{\varepsilon_{L,S}}\right)^{0.3} .\exp\left(\frac{\mathrm{Re}_L}{200}\right) \tag{12}$$

$$\mathrm{Re}_L = \frac{\rho_L v_L}{u \mu_L} \tag{13}$$

Obviously, the ratio $\frac{\varepsilon_L}{\varepsilon_{L,S}}$ becomes unity below the loading point (S). Above this point, the shear forces acting in the gas progressively support the liquid film and the liquid holdup increases until it attains a maximum in the flood point (Fl). An empirical equation has been proposed [6] to satisfy this condition:

$$\left(\varepsilon_L\right)_{v_G > v_{G,S}} = \varepsilon_{L,S} + \left(\varepsilon_{L,Fl} - \varepsilon_L\right)\left(\frac{v_G}{v_{G,Fl}}\right)^{13} \qquad (14)$$

The system of equations (4),(5), and (9) to (14) can predict the gas-side pressure drop in *a bed of any type of packing.* Obviously, after its validation by experimental data. The packing constant (C_p) is identified on this occasion. The values of $\Delta P, v_G, v_L$ are directly measured, whereas the geometric characteristics (a, ε, D, H) and the physical properties ($\rho_L, \mu_L, \rho_G, \mu_G$) are taken from the literature (Table 1). A single but very important parameter, necessary for the solution of the equations is still unknown: the liquid holdup. The use of the equation (14) needs the coordinates of the two points (load and flood points) to be known.

Loading and flooding conditions

According to the postulated fluid-dynamics model, in steady state conditions, the geometry and the shear forces within the liquid film are in equilibrium with the frictional force exercised by the gas at the interface. At a given liquid load the liquid begins to holdup when its average velocity at the interface becomes zero, i.e.:

$$u_{L,S} = 0, \qquad \text{if} \qquad x = x_0 \qquad (15)$$

This is a load point S. The equations for liquid holdup, gas loading and resistance factor in this point are presented in the ***Appendix***.

The flood point (Fl) can be identified experimentally by representing the liquid holdup against the gas load at constant liquid load. The curves becomes vertical at the flood point, i.e.:

$$\left(\frac{dv_G}{d\varepsilon_L}\right)_{v_L = v_{L,Fl}} = 0 \qquad (16)$$

The theoretical flood point correlations are also presented in the ***Appendix***. The application of these equations (17-25) together with the equation (14) for the entire range of load point in our experiments with the structured packing has lead to the diagram in Figure 4.

Now, with the coordinates of the points S and Fl determined, the equations (4), (5), and (9-14) can be applied to correlate the experimental data on pressure drop in the structured packing. This is the model validation.

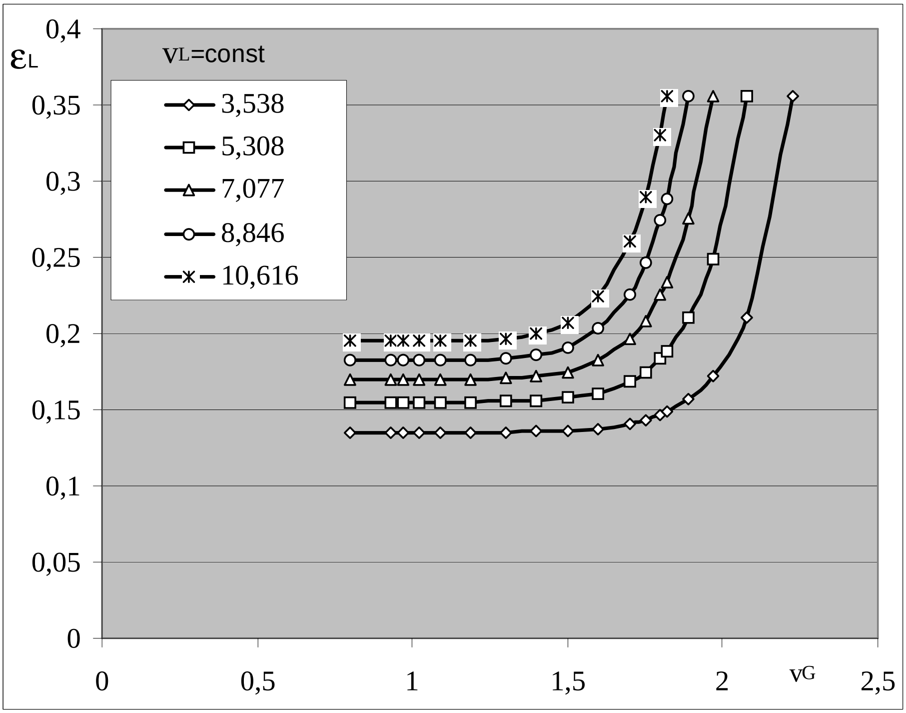


Figure 4. Relationship between the liquid holdup and the phase load in the experimental column with Mellapak 750 Y packing.

The model validation and C_p identification

The results are summarized in the Table 4. The results in Table 4 revealed that C_p is not a real constant of the packing. Its value is influenced by the liquid load. The average values of C_p for the six (I –VI) liquid loads are listed in the Table 5.

Table 4.

Calculated and experimental pressure drop at variable loading in the structured packing Mellapak 750 Y.

v_G , m/s	0.1415	0.3183	0.5305	0.7077	0.8846
Re_G	71.206	160.176	266.960	356.132	445.153
	I. V_L =50 v_L = 1.769 ε_{LS} = 0.1066				
$\Delta P / H$	30.759 C_p	106.724 C_p	257.892 C_p	430.575 C_p	643.868 C_p
$(\Delta P / H)_{exp}$	38.602	135.107	193.011	347.420	540.431
C_p	1.255	1.266	0.748	0.806	0.839
	II. V_L = 100 v_L = 3.538 $\varepsilon_{L,S}$ = 0.1353				

$\Delta P / H$	32.775C_p	113.714C_p	274.780C_p	458.781C_p	685.97C_p
$(\Delta P / H)_{exp}$	57.903	154.409	231.613	617.652	1022.961
C_p	1.767	1.357	0.841	1.346	1.491
	III. V_L = 150 v_L = 5.308 $\varepsilon_{L,S}$ = 0.1546				
$\Delta P / H$	34.471C_p	119.254C_p	288.170C_p	481.127C_p	719.461 C_p
$(\Delta P / H)_{exp}$	57.903	193.012	347.420	694.842	1196.672
C_p	1.685	1.618	1.205	1.444	1.663
	IV. V_L = 200 v_L = 7.077 $\varepsilon_{L,S}$ =0.1702				
$\Delta P / H$	35.820C_p	124.270C_p	300.060C_p	501.360C_p	749.720 C_p
$(\Delta P / H)_{exp}$	77.204	405.320	617.637	810.148	1447.586
C_p	2.155	3.262	2.058	1.616	1.931
	V. V_L = 250 v_L = 8.846 $\varepsilon_{L,S}$ = 0.1833				
$\Delta P / H$	37.171 C_p	128.970 C_p	311.650 C_p	520.380 C_p	778.080 C_p
$(\Delta P / H)_{exp}$	154.41	501.83	868.52	1158.06	1698.50
C_p	4.154	3.885	2.786	2.225	2.183
	VI. V_L = 300 v_L = 10.616 $\varepsilon_{L,S}$ = 0.1948				
$\Delta P / H$	38.458 C_p	133. 429 C_p	322.423 C_p	538.316 C_p	804.979 C_p
$(\Delta P / H)_{exp}$	193.01	636.93	1158.07	1659.90	2354.73
C_p	5.019	4.773	3.592	3.083	2.925

Table 5.

The average values of the constant C_p for the Mellapak 750Y packing.

10^3 v_L (m/s)	1.769	3.538	5.308	7.077	8.846	10.616
ε_L	0.1066	0.1353	0.1546	0.1702	0.1833	0.1948
C_p	0.983	1.360	1.522	2.204	3.046	3.878

The values of C_p in Table 5 can be correlated by the equation (26) of a straight line passing through origin:

$$C_p = 398.09\ v_L \tag{26}$$

CONCLUSIONS

The experimental results reported here show that the pressure drop per unit height in a structured packing of Mellapak 750 Y type is much smaller than that through conventional bed of Raschig rings, as expected. The data referred to the structured packing are correlated with fluid-dynamics model containing a single adjustable parameter (C_p) specific for every type of packing. The model must be valid for any type of packing if this constant is empirically identified. It has been found, in the present work, that the constant C_p is not dependent only on the packing type but also on the liquid load. This is in contradiction with the previous conclusion of Billet who stated that C_p depends only on the packing geometry and texture.

NOTATIONS

a total surface area per unit packed volume, m^2/m^3
a_u area of the unwetted surface, m^2/m^3
a_w area of the liquid surface in the flow channels, m^2/m^3
A cross sectional area of the column, m^2
C_{Fl} flood point constant, specific for the packing
C_p constant of the packing
C_S load point constant, specific for the packing
d_p equivalent diameter of the packing, m
D column diameter, m
f_w wall factor
Fl flood point
F_v gas capacity factor, $m^{-1/2}kg^{1/2}s^{-1}$
F_w wetting degree
g acceleration due to gravitation, m/s^2
H effective height of column packing, m
K integration constant in the Eqn(1)
m_L liquid mass flow rate, kg/s
m_G gas flow rate, kg/s
n exponent
P total pressure, Pa
ΔP pressure drop, Pa or mm WG
Re_G Reynolds number of the gas phase, Eqn(9)
Re_L Reynolds number of the liquid phase, Eqn(13)
S load point
u_G average gas velocity, m/s
u_L average liquid velocity, m/s
v_G gas load, m^3/m^2s
v_L liquid load, m^3/m^2s
V_G gas flow rate, m^3/s
V_L liquid flow rate, m^3/s
x thickness of the liquid film, m

Greek symbols

ε_L liquid holdup
$\varepsilon_{L,Fl}$ liquid holdup in the flood point
$\varepsilon_{L,S}$ liquid holdup in the load point
ε total void fraction of the packing
μ_G dynamic viscosity of the gas, Pa s
μ_L dynamic viscosity of the liquid, Pa s
ζ_{Fl} coefficient of resistance at the flood point
ζ_L coefficient of resistance in the irrigated packing
ζ_0 coefficient of resistance to flow in the unwetted bed
ζ_S coefficient of resistance in the load point
ρ_G gas density, kg/m^3
ρ_L liquid density, kg/m^3

Subscripts

Fl flood point
S load point
L liquid phase
G gas phase
p packing (in the constant C_p)
W wall (in wall factor), wetting (in F_v), wetted (in a_w)
v vapor or gas.

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APPENDIX

Load point (S)

In the load point the liquid phase begins to holdup when its velocity at the interface ($x = x_0$) becomes zero. The corresponding gas velocity is the upper limit for the absolutely stable hydrodynamic range, defined by [9,10]:

$$v_{G,S} = (\varepsilon - \varepsilon_{L,S})\sqrt{\frac{\varepsilon_{L,S}\, g \rho_L}{\zeta_S\, a \rho_G}} \qquad (17)$$

The application of the equation (17) requires the knowledge of the liquid holdup at the load point ($\varepsilon_{L,S}$) and the corresponding resistance factor(ζ_S).These can be predicted by the equations (18) and (19) respectively [10]:

$$\varepsilon_{L,S} = \left(\frac{12}{g} a^2 \frac{\mu_L}{\rho_L} v_L\right)^{1/3} \qquad (18)$$

$$\zeta_S = \frac{g}{C_S{}^2}\left[\frac{m_L}{m_G}\left(\frac{\rho_G}{\rho_L}\right)^{1/2}\left(\frac{\mu_L}{\mu_G}\right)^{0.4}\right]^{2n_S} \qquad (19)$$

It has been found that the following empirically determined numerical values of the exponent n_S usually apply for all types of packing in the loading ranges concerned [7]:

when: $\frac{m_L}{m_G}\left(\frac{\rho_G}{\rho_L}\right)^{0.5} \leq 0.4$ $\qquad n_S = 0.326 \qquad (20)$

when: $\frac{m_L}{m_G}\left(\frac{\rho_G}{\rho_L}\right)^{0.5} > 0.4$ $\qquad n_S = 0.723 \qquad (21)$

Numerical values of the constant C_S for specific types of randomly dumped as well as systematically stacked packings are listed in tables [8]. A value $C_S = 3.157$, determined for Mellapak 250 Y has been adopted to predict $\varepsilon_{L,S}$ for our Mellapak 750Y. This is the weak point of the calculations in the present work.

Flood point (Fl)

The curves ε_L versus v_G become vertical at the flood point. The general equation derived from the fluid dynamic model becomes of the following form in the flood point:

$$\varepsilon^3{}_{L,Fl}\left(3\varepsilon_{L,Fl}-\varepsilon\right)=\frac{6}{g}\frac{m_l}{m_G}\frac{\rho_G}{\rho_L}\frac{\mu_L}{\mu_G}a^2\varepsilon v_{G,Fl} \quad (22)$$

The right hand-side of this equation must be positive. This implies that the liquid holdup at the flood point has not to be less than $\varepsilon/3$ and must lie only within the limits:

$$\frac{\varepsilon}{3}\le\varepsilon_{L,Fl}\le\varepsilon \quad (23)$$

It has been found that for liquid loading between 0.1 and 200 m^3/m^2h, $\varepsilon_{L,Fl}$ can be evaluated by:

$$\varepsilon_{L,Fl}=0.3741\varepsilon\left(\frac{\mu_L\rho_{H_2O}}{\rho_L\mu_{H_2O}}\right) \quad (24)$$

The resistance factor at the flood point is given by[1]:

$$\zeta_{Fl}=\frac{g}{C^2{}_{Fl}}\left[\frac{m_L}{m_G}\left(\frac{\rho_L}{\rho_G}\right)^{0.5}\left(\frac{\mu_L}{\mu_G}\right)^{0.2}\right]^{2n_{Fl}} \quad (25)$$

where:

$n_{Fl} = 0.194$ when: $\frac{m_L}{m_G}\left(\frac{\rho_G}{\rho_L}\right)\le 0.4$ (26)

$n_{Fl} = 0.708$ when: $\frac{m_L}{m_G}\left(\frac{\rho_G}{\rho_L}\right)> 0.4$ (27)

Similarly, the constant C_{Fl} has been adopted from the literature (C_{Fl} = 2.464) for Mellapak 250Y, the only structured packing already studied [7].
The gas load in the flood point has been determined with the equation [10]:

$$v_{g,Fl}=\sqrt{\frac{\left(\varepsilon-\varepsilon_{L,Fl}\right)^3}{\varepsilon}}\left(\frac{2g\rho_L\varepsilon_{L,Fl}}{\zeta_{Fl}a\rho_G}\right)^{1/2} \quad (28)$$

The liquid holdup at loading between the point S and the point Fl has been calculated with the empirical equation (14) using the data in Figure 4 for S and Fl.