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PRESENT A MODERN
LIQUID DISTRIBUTOR AND
REDISTRIBUTOR DESIGN.

ALL THE MOD CONS

PART 1

In recent years, great efforts have been made to design structured and random packings for mass transfer columns more and more effectively, i.e. to achieve greater throughputs, lower pressure drops and better mass transfer efficiencies. These advantages are only effective if, at the same time, modern internals are used. Of all internals, the liquid distributors are the most significant ones since they play a decisive part in influencing the mass transfer efficiency of structured or random packings. An uneven distribution of the liquid phase, initiated by the liquid distributor, is compensated only to a minor degree within a structured or random packing, since the liquid flows downwards due to gravity. Consequently, local differences in liquid/vapour ratios occur, which can reduce the column's mass transfer efficiency markedly.¹⁻¹⁰

This article is divided into two parts. Part 1 discusses what factors influence the design of a liquid distributor and how detailed the fluid dynamic and mechanical design must be in order to avoid a failure in the mass transfer efficiency of modern packings. Part 2 explains the impact of distribution quality on separation efficiency and shows failures recognised in industrial columns.

Theoretical fundamentals

The basis of any distributor design is the exact knowledge of the discharge behaviour of liquids from round holes and lateral rectangular slots or triangular notches. The following refers to circular ground orifices but can be applied analogously to rectangular slots or triangular notches as well. The fundamentals of the discharge behaviour of fluids out of circular openings stretch back to the year 1644, where Torricelli developed Equation 1.



$$w_{th} = \sqrt{2gh} \quad (1)$$

Equation 1 describes the theoretical discharge velocity of liquids, w_{th} , from orifices as a function of the gravitational acceleration, g , and the liquid head above the orifice, h . If one multiplies this theoretical velocity, w_{th} , by the cross-sectional area of a hole, A_h , and the number of discharge holes of a liquid distributor, n , then one achieves the theoretical total volume rate, \dot{V}_{th} , which can flow out of a liquid distributor (Equation 2).

$$\dot{V}_{th} = A_h \cdot n \cdot \sqrt{2 \cdot gh} \quad (2)$$

Equation 2 applies under ideal conditions, i.e. assuming that the flow through the hole imparts no resistance to the flow of liquid. But in reality, streamlines of different velocities are formed due to the sharp edged holes which cause deflection of the liquid jet flow (Figure 1).

For describing the flow behaviour of the liquid jet flow, one has to interpret two effects. First the jet contraction and second the jet velocity. The orientation of the streamlines causes the jet of liquid to contract when it leaves the ground hole. This effect can be described mathematically by a contraction coefficient, C_c . Friction losses, caused by shearing forces of the fluid, influence the velocity of the jet of liquid when it issues through the hole and can be described mathematically by a velocity coefficient, C_v . The coefficients depend on the liquid head, the hole geometry and the physical properties of the liquid.

The product of the contraction coefficient, C_c , and the velocity coefficient, C_v , results in the discharge coefficient, $C_D = C_c \cdot C_v$, which describes the difference between the effective volume rate, \dot{V} , and the theoretical value, \dot{V}_{th} . Only the discharge coefficient, C_D , can be derived from experimental investigations directly.

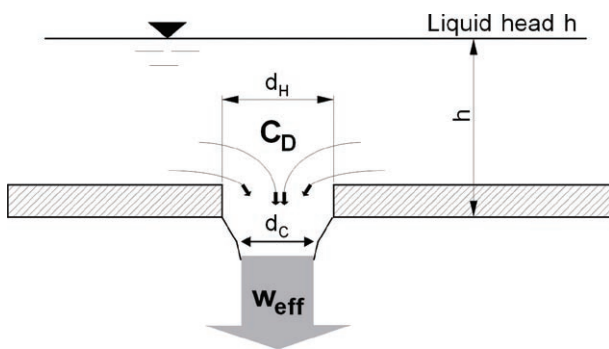


Figure 1. Liquid jet flow out of sharp edged holes in liquid distributors.

$$\dot{V} = C_D \cdot A_h \cdot n \cdot \sqrt{2 \cdot gh} \quad (3)$$

The discharge coefficient, C_D , is described in the literature according to Table 1 as a constant value in function of the hole geometry only.

Actual discharge behaviour

If one describes the flow through a hole on the basis of an energy balance, equilibrium can be set up according to Equation 4. The inflowing volume, \dot{V} , acts on the hole with the potential energy $(\rho_L - \rho_v)gh$ while the out flowing volume rate \dot{V} leaves the hole as a jet flow with the kinetic energy $(\rho_L w^2/2)$. The energy of the jet leaving the hole is less than that of the inflowing liquid since the contraction and friction loss of the jet has consumed energy characterised by \dot{E} in Equation 4.

$$(\rho_L - \rho_v)g \cdot h \cdot \dot{V} = \frac{\rho_L}{2} \cdot w^2 \cdot \dot{V} + \dot{E} \quad (4)$$

In Equation 4, ρ_L describes the liquid density and ρ_v the gas density; g describes the gravitational acceleration, h describes the liquid head above the hole, and w describes the current velocity of the jet.

By including Equation 3 in Equation 4, Equation 5 follows for the coefficient of discharge C_D . The second term of the right side of Equation 5 describes the energy consumption E divided by the potential energy for a certain liquid head above the hole h and for a volume flow rate \dot{V} . The energy consumption E tends to zero for low flow rates. Consequently, the coefficient of discharge C_D tends to unity for low flow rates in case the gas density can be neglected compared to the liquid density.




$$C_D = \sqrt{\frac{\rho_L - \rho_v}{\rho_L} - \frac{E}{\rho_L \cdot g \cdot h \cdot \dot{V}}} \quad (5)$$

Systematic investigations have shown that the discharge coefficient, $C_D = C_c C_v$ is a variable which is dependent on several influencing parameters. An expression for the energy consumption E was evaluated that allows an accurate prediction of the coefficient of discharge C_D .

Following the influencing parameters on the overall coefficient of discharge, C_D , will be discussed in detail (Figure 2).

Figure 2 shows measurement points for the discharge coefficient, C_D , for water at ambient temperature as a function of the liquid head, h , for various hole diameters, d . It also shows the constant $C_D = 0.62$ recorded in the literature for holes whose dimensions are larger than the depth of the hole.¹² It can be clearly seen that the discharge coefficients only approximate the value given in the literature if the liquid head is great and hole diameters large.

With decreasing liquid head, the discharge coefficient rises significantly with the result that the discharge behaviour with small liquid head deviate more favourable from discharge behaviour according to Table 1 than with large liquid head. This can be explained by the fact that as the liquid

Shape of the orifices	Coefficient of velocity C_v	Coefficient of contraction C_c	Coefficient of discharge C_D
	0.97	0.61.....0.64	0.59.....0.62
	0.97.....0.99	~1	0.97.....0.99
	~0.82	~1.0	~0.82

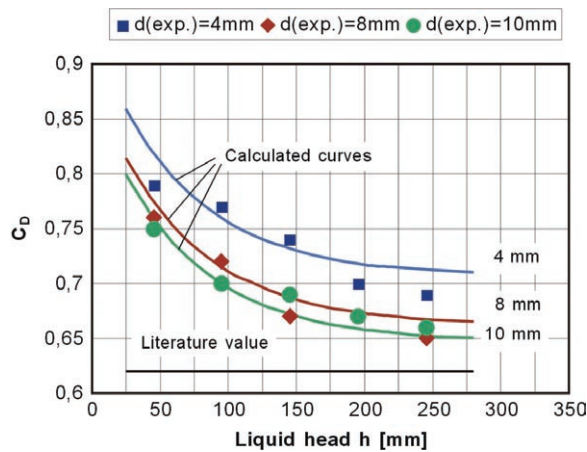


Figure 2. Coefficient of discharge as a function of liquid head for various hole diameters and aqueous system: $\rho_L = 998 \text{ kg/m}^3$; $\mu_L = 1 \text{ mPas}$; $\sigma_L = 73 \text{ mN/m}^2$.

head decreases, the horizontal velocity component decreases and therefore a reduction of the contraction of the jet occurs. Figure 2 also shows that with decreasing hole diameter, the discharge coefficient rises, i.e. the contraction is reduced by the counteraction of the horizontal velocity components.

In case of small liquid heads, tensile forces of the jet are also transferred even into the hole cross-section, with the result that the liquid is drawn out of the opening and, if the liquid level is calm, a vortex is formed. This effect is more marked in the case of large hole geometries than in the case of small hole geometries, as can be seen from the steeper curves in Figure 2 at low liquid heads.

The relationships described only apply if the influence of the surface tension is negligible. For instance, in case of small holes and liquids with a high surface tension, a drop of liquid is formed beneath the hole, preventing the fluid from flowing out. Further factors that are influencing the coefficient of discharge but not discussed here are physical properties of the fluid (density, viscosity), elevation and orientation of holes, overflow velocity and ratio of hole diameter to deck thickness.

The dimensioning of liquid distributors

In the dimensioning of liquid distributors, not only the discharge coefficient but also other design determining criteria have to be taken into account. In that manner, first the minimum liquid head, h_{\min} , above a discharge hole of a liquid distributor must be determined. Here the flow velocity of the liquid in the distributor troughs is of decisive importance since flow gradients occur due to wall friction and lead to significant differences in height, particularly in case of low liquid heads. If these minimum liquid heads are not attained, considerable maldistribution of a distributor can occur, as described as follows.

The minimal liquid level in a distributor

Feeding liquid into a mass transfer column generally takes place via a feed pipe which first leads the liquid into a preliminary distribution trough called a parting box. Afterwards, the liquid reaches the individual distributor troughs lying below and flows in the troughs towards the column wall. Drag, due to wall friction, causes liquid head gradients to form in the distributor troughs, which has to be taken into account, particularly with low liquid levels. This is illustrated in Figure 3.

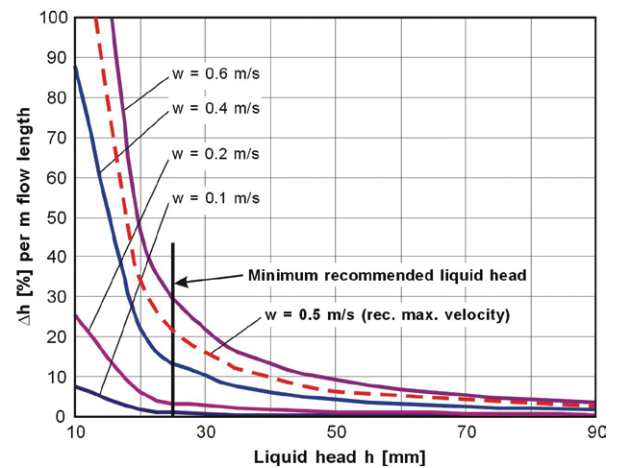


Figure 3. Difference in liquid height, Δh , per m trough length as a function of liquid head, h , in a trough type distributor at various flow velocities, w , along the trough for water at ambient temperature.

For liquid flow in open trough systems the difference in height, Δh , taking place along the trough can be calculated using Equation 6. It is a function of the wall friction factor, λ , hydraulic diameter, d_h , gravitational acceleration, g , and flow velocity. Figure 3 shows the result of such a calculation for a trough with a width of $b = 100 \text{ mm}$ for various flow velocities as a function of the liquid head, h .

$$\Delta h = \lambda \cdot \frac{1}{d_h} \cdot \frac{w^2}{2 \cdot g} ; d_h = 4 \cdot \frac{A}{U} = 4 \cdot \frac{h \cdot b}{b + 2 \cdot h} \quad (6)$$

The following recommendations for the minimum liquid level, h_{\min} , in distributor troughs can be derived from the observations of Figure 3. The minimum liquid head should not fall short of a value of 25 - 35 mm and at the same time the flow velocity in the troughs should be limited to a maximum of 0.5 m/s. Furthermore, the liquid head should be equivalent to at least twice the hole diameter in order to avoid vortex formation above the hole (Equation 7).

$$h_{\min} > 25 - 35 \text{ mm or } h_{\min} > 2 \cdot d_H \text{ which ever is greater for } w < 0.5 \text{ m/s} \quad (7)$$

The overall height of a distributor

The overall height of a liquid distributor is first defined by the required liquid loading range. To this height, the hydrostatic pressure occurring as the result of the pressure drop of the gas phase as this passes the troughs of the distributor must be added. Furthermore, additional height is necessary if a foaming system is present and if a noticeable gas rate is injected into the liquid at the liquid feed point. The latter applies particularly in the case of high pressure systems if the degassing of the liquid is markedly restricted due to the small differences in density between the gas and the liquid. Furthermore, wave formation has to be taken into account in the case of flowing liquids.

Liquid loading range

By converting Equation 3, Equation 8 can be obtained which defines the necessary extra height, Δh_1 , of a liquid distributor resulting from a required loading range.

$$\Delta h_1 = \left[\left(\frac{\dot{V}_{\max}}{\dot{V}_{\min}} \right)^2 \cdot \left(\frac{C_D(h_{\min})}{C_D(h_{\max})} \right)^2 - 1 \right] \cdot h_{\min} \quad (8)$$

When calculating the necessary extra height, Figure 2 must be taken into account showing that the discharge coefficient, C_D , provides larger values with the lower liquid head than with the higher liquid head. This yields greater overall heights than if a constant discharge coefficient is assumed.

Gas phase pressure drop

The pressure drop, which the gas flow undergoes when it passes through the narrowed distributor cross-section, can be calculated by Equation 9. ξ is the drag coefficient for the sudden narrowing and expansion of flows, F_v is the gas capacity factor in the column, A_c is the cross-sectional area of the column and A_D is the free cross-sectional area of the distributor.

$$\Delta p = \frac{\xi}{2} \cdot \frac{A_c^2}{A_D^2} \cdot F_v^2 \quad (9)$$

$$\Delta p = (\rho_L - \rho_v) \cdot g \cdot \Delta h_2 \quad (10)$$

This pressure drop causes a rise in hydrostatic pressure to the head of liquid in the distributor, which can be described with the aid of Equation 10. By equating Equation 9 and Equation 10, Equation 11 can be obtained for the description of the second portion, Δh_2 , for the overall height of a distributor.

$$\Delta h_2 = \frac{1}{(\rho_L - \rho_v) \cdot g} \cdot \frac{\xi}{2} \cdot \frac{A_c^2}{A_D^2} \cdot F_v^2 \quad (11)$$

Foaming system

In the case of a foaming system, the foam will be built up in particular in those areas in which a marked gas injection into the liquid takes place. This applies particularly to the transfer of the liquid from the feed pipe into the parting box, since relatively large quantities of liquid are transferred per transition point. Since the description of the foaming behaviour is very complex, it is advisable to use the foam or system factor, Ψ , which is described in the literature.¹³ This empirical factor is known for numerous mass transfer tasks and has to be taken into account by Equation 12, based on empirical equation, for the calculation of the additionally necessary distributor height, Δh_3 .

$$\Delta h_3 = f\left(\frac{1}{\Psi}\right) \quad (12)$$

One must notice that system factors, listed in the literature, result from long term experience in designing tray columns and includes foaming and degassing effects in parallel. Experience is needed for avoiding overdesigns in taking system factor and degassing into account in parallel. The increase of liquid distributor height can, however, be markedly restricted if design methods are taken into account to reduce foaming. For instance, immersed elongated guide pipes at the feed pipe can be used to feed the liquid into the liquid level of the parting box and thus reduce foaming. Alternatively, guide sheets can be used as impulse dampers above the parting box, or a package of structured or random packings can be used within the parting box or distributor trough in order to support separation of gas and liquid.

Degassing

As has already been described, the high impulse transfer as liquid passes from the feed pipe into the parting box, causes gas also to be introduced with the jets of liquid into the liquid layer. The gas then occupies a noticeable volume in the amount of liquid, which causes the liquid level in the trough to rise. The additional extra height this requires is determined by the gas portion introduced and by the residence time of the gas in the liquid. The degassing behaviour is essentially defined by the buoyancy of the gas bubbles, i.e. by the difference in density between the gas and the liquid. Particularly in high pressure applications the density differences are small and therefore the degassing efficiency reduced. As is the case with foaming systems, the additional height, Δh_4 , which must be taken into account on the basis of the degassing behaviour can, until now, only be described on the basis of an empirical equation (Equation 13).

$$\Delta h_4 = f\left(\frac{\rho_L}{\rho_L - \rho_v}\right) \quad (13)$$

The degassing of liquids can, however, be improved by design methods, similar to foaming behaviour.

Wave formation

If the liquid is led from the distributor pipe into the parting box and then into the distributor troughs, the impulse transfer causes wave formation which is supported by the flow of the liquid in the troughs. The overall height of a distributor must be dimensioned so that the wave crests do not lead to a flooding of the distributor troughs or gas risers.


Since the wave formation depends on the quantity of liquid to be distributed, it is advisable to design the additionally necessary distributor height, Δh_5 , according to Equation 14 as an empirical function of the liquid load.

$$\Delta h_5 = f(u_L) \quad (14)$$

Taking all the single heights into account, the necessary overall height is defined according to Equation 15.

$$H_{\text{Total}} = h_{\text{min}} + \Delta h_1 + \Delta h_2 + \Delta h_3 + \Delta h_4 = \Delta h_5 \quad (15)$$

Conclusion

Modern liquid distributor designs are relevant for good mass transfer efficiencies in packed columns. The article describes the flow behaviour of a liquid jet flow that is leaving a distributor via bottom holes. An equation is provided to describe the coefficient of discharge and influencing parameters are discussed. The height of a distributor trough has to take into account the recommended minimum liquid head, specified liquid loading range, gas pressure drop, foaming and degassing effects and wave creations. This subject is described as well. 

Nomenclature

A	m ²	Area
A _c	m ²	Free column cross-section area
A _D	m ²	Free distributor cross-section area
A _h	m ²	Hole area
b	m	Width
C _c	-	Coefficient of contraction
C _D	-	Coefficient of discharge

C_v	-	Coefficient of velocity
d_c	m	Diameter of contraction
d_H	m	Hole diameter
d_h	m	Hydraulic diameter
E	Nm/s	Rate of dissipation of energy as a result of jet flow
F_v	\sqrt{Pa}	Vapour capacity factor: $u_v \cdot \sqrt{p_v}$
g	m/s ²	Gravitational acceleration
h	m	Liquid head
n	-	Number of holes
p	Pa	Pressure
U	m	Circuit
u_v	m/s	Superficial vapour velocity
\dot{V}_{th}	m ³ /s	Theoretical liquid volume flow
\dot{V}	m ³ /s	Volume flow
w	m/s	Velocity of liquid
w_{th}	m/s	Theoretical liquid velocity
Δ	-	Differential term
η_L	mPa/s	Dynamic viscosity
Ψ	-	Foam or system factor
λ	-	Wall flow friction factor
ρ_L	kg/m ³	Liquid density
ρ_v	kg/m ³	Vapour density
σ_L	mN/m ²	Surface tension
ξ	-	Drag coefficient

Acknowledgements

Sadly, Michael Rink passed away after the writing of this article.

References

1. LOCKET, M. J., BILLINGHAM, J. F., 'The effect of maldistribution on separation in packed distillation columns'; Distillation & Absorption, Baden-Baden/Germany, 2002.
2. SCHULTES, M., 'Influence of liquid redistributors on the mass transfer efficiency of packed columns', Ind:Eng.Chem.Res. Vol. 39, No. 5, p. 1381 - 1389, 2000.
3. STIKKELMAN, R. M., 'Gas and Liquid Maldistributions in Packed Columns', Academisch Boeken Centrum, 1989.
4. ZUIDERWEG, F. J., HOEK, P. J. and LAHM, L. Jr., 'The Effect of Liquid Distribution and Redistribution on the Separating Efficiency of Packed Columns', I.Chem.E.Symposium Series No. 104, 1987.
5. STIKKELMAN, R. M. and WESSELINGH, J. A., 'Liquid and Gas Flow Patterns in Packed Columns', I.Chem.E.Symposium Series No. 104, 1987.
6. KOURI, R. J. and SOHLO, J. J., 'Liquid and Gas Flow Patterns in Random and Structured Packing', I.Chem.E.Symposium Series No. 104, 1987.
7. ZUIDERWEG, F. J. and HOEK, P. J., 'The Effect of Small Scale Liquid Maldistribution ('Natural Flow') on the Separating Efficiency of Random Packings', I.Chem.E.Symposium Series No. 104, 1987.
8. PORTER, K. E. and JONES, M. C., 'Liquid and Gas Distribution in the Scale-up of Packed Columns', I.Chem.E.Symposium Series No. 104, 1987.
9. HUBER, M. and MEIER, W., Methode zum Messen der Maldistribution in Füllkörperkolonnen', Chem.-Ing.-Tech., 1967.
10. HILTBRUNNER, R. and HUBER, M., Füllkörper-Rektifizierkolonnen mit Maldistribution', Chem. Eng. Sci., 1966.
11. BOHL, W., Technische Strömungslehre', Vogel-Verlag, Würzburg, 1975.
12. PERRY, R. H. and GREEN, D. W., 'Perry's Chemical Engineer's Handbook', McGraw-Hill, New York, 1997, p. 6 - 22.
13. KISTER, H. Z., 'Distillation Design', McGraw-Hill, New York, 1992.