Design of Direct-cooling Plant

by

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Design of Direct-cooling Plant

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The uses of direct-contact equipment are perhaps greater than for any other type of heat transfer plant when rapid rates of heat transfer are required. Both heat and mass are transferred, but mass transfer coefficients in industrial towers differ widely from those found in laboratory tests and packed towers are necessarily overdesigned because of the sparsity of reliable design information and uncertainty of operation. In the first part of this article the design method for direct coolers is reviewed and discussed for the case in which a hot inert gas is cooled in direct contact with cooling water, the vapour pressure being small when compared with the total superimposed pressure. For this particular case the available theoretical treatments reduce to one general design method which is considered to meet the designer's needs adequately. In the second part of the paper the properties of packed beds are discussed. It is concluded that the wall-effect, which is the effect of the tower wall on the bulk density of the packing, is explained by the way in which the tower wall supports the packing, thus preventing compaction.

A correlation of voidages in packed beds based on this hypothesis correlates the data.

THE general equations[1, 2] which cover the thermal design method are well known and hence the setting up of the basic differential equations is not discussed here. Sensible heat transfer and heat transfer by mass diffusion proceed according to equations (1) and (2), respectively. The overall heat balance yields equation (3):

$$\delta Q_s = G.\,c_g.\,\delta T = h_g.\,a\,(T-t)\,\delta Z \quad (1)$$

$$\delta Q_d = \lambda.\,\delta L = k_x.\,a\,(X-X_t).\,\lambda.\,\delta Z \quad (2)$$

$$G.\,\delta H = L.\,c_l.\,\delta t \quad (3)$$

For water we have $c_l = 1$, and

$$\frac{\delta H}{\delta t} = \frac{L}{G} \quad (3a)$$

Adding equations (1) and (2) to obtain the overall heat transfer:

$$\delta Q = L.\,\delta t = G.\,\delta H = \delta Q_s + \delta Q_d \quad (4)$$

$$= G.\,c_g.\,\delta t + \lambda.\,\delta L \quad (4a)$$

$$= h_g.\,a\,(T-t)\,\delta Z + k_x.\,a\,(X-X_t).\,\lambda.\,\delta Z \quad (4b)$$

From the Chilton and Colburn analogy,[3] as quoted by Kern,[4] we obtain a relation between h_g and k_x:

$$h_g = k_x.\,c_g.\,\mathrm{Le} \quad (5)$$

where Le is the Lewis number. On the assumption that less heat is transferred by diffusion compared with sensible heat transfer we can, by means of equation (5), eliminate k_x from equation (4*b*), and add, so obtaining the relation below. We can equally well make the opposite assumption, as the case demands it, and then eliminate h_g from equation (4*b*).

$$\delta Q = L.\,\delta t = h_g.\,a\left[(T-t) + \frac{(X-X_t)\,\lambda}{c_g\,\mathrm{Le}}\right]\delta Z \quad (6)$$

$$= \frac{h_g.\,a}{c_g}\,(H-H_t)\,\delta Z \quad (7)$$

where

$$H = c_g\,(T-t_o) + X.\,\lambda \quad (8a)$$

$$H_t = c_g\,(t-t_o) + X_t.\,\lambda \quad (8b)$$

H is the enthalpy of the gas and H_t is the enthalpy of saturated gas at water temperature. $(H-H_t)$ is the 'total heat' or enthalpy driving force. From equation (7) we have

$$\delta n = \frac{\delta t}{H-H_t} = \frac{h.a}{L.\,c_g}\,\delta Z \quad (9)$$

By definition:

n = number of diffusion units

$$= \int\frac{\delta t}{H-H_t}$$

so that

$$\int\frac{\delta t}{H-H_t} = n = \frac{h.a}{L.\,c_g}\,Z \quad (10)$$

that is,

$$Z = \frac{n.\,L.\,c_g}{h.\,a} \quad (11)$$

The number of diffusion units is generally and conveniently evaluated graphically. The packing characteristic *ha* being known, the depth of packing may then be calculated. The graphical method consists of plotting H and H_t versus t, whence $1/H-H_t$ may be integrated with respect to t, by plotting $1/H-H_t$ versus t and then counting squares. The integration may also be carried out numerically.

It is as well, however, to appreciate the underlying assumptions which are inherent in the above derivation of the design relations. These are:

(1) The analysis is based on one square foot of tower cross-sectional area.

(2) A positive rate of transfer indicates that transfer is taking place from gas towards the cooling liquid, as is in general the case for direct coolers.

(3) A steady state has been reached throughout the depth of packing, and is maintained.

(4) No heat is lost to, or gained from, the surroundings. With even reasonable distribution the wall temperature of a direct cooler operating in part at a gas temperature of 700°F. or so remains relatively cool, at near cooling water temperature. If required, then Kern's stepwise method[4] may readily be modified to allow for heat exchange between the cooler and surroundings.

(5) Conditions are constant over any cross-section of the cooler, perpendicular to the direction of flow. This involves assuming uniform liquid and gas distribution and ignores the so-called 'wall effect', which is discussed further on. Although uniform distribution may be a problem on the laboratory scale, it is considered that reasonable distribution is in general obtained in full-scale equipment, provided that some thought has been put into the design of the liquid distributor, at the liquid rates which are required to ensure that the packing is wetted reasonably well.

(6) Fluid velocities are determined by considerations other than those taken into account whilst establishing the design relations. Examples are the economic or permissible pressure drop on the gas side and the need to wet the packing effectively. Pratt[13] has shown that degree of wetting depends on liquid flow-rate, up to a point. There is a 'minimum effective liquid rate' which is the lowest rate at which the packing is effectively wetted.

(7) No chemical reaction occurs.

(8) The subscript g to the heat-transfer coefficient h indicates that the gas film is controlling so that the liquid film resistance is by comparison so small as to be negligible.[33] Hence h_g, the gas-film heat transfer coefficient, is the overall point heat transfer coefficient. This is a reasonable assumption for the system inert gas/water.

(9) As the partial pressure of the vapour is small when compared with the inert gas pressure, it is assumed that mass transfer by diffusion does not appreciably affect the gas velocity. Hence the effect of velocity changes on the transfer coefficients is neglected. It is further assumed that coefficients are constant with respect to temperature and thus with respect to packed depth so that the point coefficients are taken to be overall coefficients.

(10) Mass transfer by diffusion is taken to be negligible when compared with total liquid flow-rate, which is therefore assumed to remain constant throughout the tower. Assuming constancy of flow-rates is, in general, justified for direct coolers, but effect of variation in flow-rates can be allowed for by Kern's method.[4]

(11) The relationship expressed by equation (5) is based on the Chilton and Colburn analogy between fluid friction and mass transfer. The precise relation is not established with certainty and hence the relationship is applied to the smaller of the two heat transfer rates.

(12) It is assumed that Lewis number = 1. For an air/water system, the Lewis number ranges from about 0.9 to 1.0, but it may differ appreciably from 1 for other systems. Again, Kern's method[4] enables one to allow for variation in (Le) throughout the tower.

(13) It is in general a reasonable assumption to make in the case of direct coolers that the partial pressure of the vapour is negligible when compared with the inert-gas pressure. The mean inert-gas pressure across the gas film then closely corresponds to the total pressure; and the 'humidity' driving force, rather than a partial-pressure driving force, together with the corresponding 'humidity' diffusional mass transfer coefficient may be used. It is convenient to do so.

(14) The effect of superimposed pressure[11, 12] on the equilibrium vapour pressure is neglected. It becomes

NOMENCLATURE

a = Specific surface of packing (sq.ft./cu.ft. packed space)
c = Specific heat (B.T.U./lb.°F.)
c_g = Humid heat of gas/vapour mixture (B.T.U./°F. lb. inert gas)
d = Nominal diameter of packing unit (ft.)
d_i = Internal diameter of packing unit (ft.)
d_o = Outside diameter of packing unit (ft.)
d_p = Characteristic dimension of packing unit (defined differently by different investigators)
D = Internal diameter of shell of packed tower (ft.)
G = Inert gas mass flow-rate (lb./hr. ft.^{2} tower c.s.a.)
h = Convection heat transfer coefficient (B.T.U./hr. ft.^{2} °F.)
h_g = Convection gas-film heat transfer coefficient (B.T.U./hr. ft.^{2} °F.)
H = Enthalpy of gas/vapour mixture (B.T.U./lb. dry gas)
H_t = Saturation enthalpy of gas/vapour mixture (B.T.U./lb. dry gas)
k = Ratio between lateral and vertical pressures exerted by a packed bed
k_x = Diffusion mass-transfer coefficient (lb./hr. ft.^{2} lb./lb.)
l = Length of packing unit (ft.)
L = Cooling water mass flow-rate (lb./hr. ft.^{2} tower c.s.a.)
(Le) = Lewis number
n = Number of diffusion units
P = Pressure (lb./sq.ft.)
Q = Heat transfer rate (B.T.U./hr. ft.^{2} tower c.s.a.)
R = Mean hydraulic radius of tower shell (ft.)
t = Water temperature (°F.)
t_o = Enthalpy reference temperature (°F.)
T = Gas temperature (°F.)
X = Humidity of gas (lb. vapour/lb. dry gas)
X_t = Saturation humidity of gas at water temperature (lb. vapour/lb. dry gas)
X_T = Saturation humidity of gas at gas temperature (lb. vapour/lb. dry gas)
Z = Depth of packing (ft.)
δ = Differential increment
ε = Fractional voidage of packed bed
ε' = Free fractional voidage of packing, here estimated from manufacturers' data
θ = Angle of slip of packing material on wall of containing shell (degrees)
λ = Latent heat of vaporisation (B.T.U./lb.)
μ = Coefficient of friction, packing material to wall of containing vessel (= $\tan\theta$)
ρ = Apparent bulk density of packing in the packed tower (lb./cu.ft.)
ρ_p = Density of solid material of which the packing unit is constructed (lb./cu.ft.)
ϕ = Angle of internal friction of packing (angle of repose for perfect granular material) (degrees)

Suffixes:
d = Diffusional heat transfer
l = Pertaining to liquid
L = Lateral
o = Reference level
s = Sensible heat transfer
t = At temperature t
V = Vertical

significant at pressures above 10 atm. and can be allowed for by correcting the calculated humidities.

(15) Equation (1) allows for changes in sensible heat content of the vapour, as c_g is the humid heat. In equation (2) it is assumed that latent heat only is transferred by mass diffusion. Bras[5, 6] has worked out a method of allowing for the sensible heat content of the diffusing vapour.

(16) In equations (8*a*) and (8*b*) the total heat, apart from the sensible heat content of the dry gas, includes the sensible heat content of the water vapour from base to gas temperature, plus the latent heat content of the water vapour. Sherwood and Reed[7] and McAdams[8] assume that the water evaporates at base temperature. Carey and Williamson,[9] and Wood and Betts,[10] assume that the water evaporates at the dewpoint, or gas temperature, for unsaturated and saturated gas, respectively. Kern[4] calculates enthalpies by assuming, for saturated gas, that water is heated up to the gas temperature and evaporates at that temperature. For unsaturated gas he assumes that water is heated up to the dewpoint, evaporates at the dewpoint, and that the vapour is then superheated to the gas temperature. Kern's method is preferred, as it appears to correspond more closely to the process of condensation occurring in a direct cooling tower, but such inconsistencies are not thought to affect the ultimate design one way or another.

(17) There is a lack of reliable knowledge concerning transfer coefficients. Published data are scarce, obtained in the laboratory rather than on industrial installations, and there is no correlation known to the author by which the transfer coefficients for packed towers may be estimated with any reasonable degree of confidence. So far it does not appear to have been possible to correlate coefficients after duly allowing for differences in wetted area, or vice versa, so that coefficients based on unit volume of packed tower have to be used.

The amount of surface that is actually packed into a given space seems rarely to have been measured.

(18) Carey and Williamson[9] go through very much the same procedure in deriving design equations as those given above. However, they use a partial-pressure driving force and express moisture content in terms of volume ratios, their steam ratio being the ratio of the volume of water vapour present to that of inert gas. They make the same assumptions as those stated here, which applies particularly to the case where vapour pressure is negligible compared with inert gas pressure so that the drift-factor may be ignored, when no advantage is to be gained by using transfer coefficients based on vapour pressure rather than on humidity driving forces. Their factor f is the Lewis number and is assumed by them also to equal unity. Hence, throughout, Carey and Williamson's method, by algebraic conversion to the units used here, may be reduced to the same method as that above. Similarly, the method of Wood and Betts[10] may be shown to be the same.

Carey and Williamson assume sensible heat transfer to be small compared with diffusional mass transfer and thus convert the sensible heat transferred to an equivalent amount of heat transfer by diffusion. On the other hand, Wood and Betts assume that diffusion of mass accounts for the smaller quantity of heat transferred and thus convert it to sensible heat. To that extent the authors are restricting the usefulness of their treatment as compared with the more general one, where such an assumption is made as the case demands.

(19) Kern[4] gives a step-by-step method of calculating the number of diffusion units. This method may be used as it stands, Kern illustrating how to carry out the calculation without assuming that the Lewis number equals unity. It may readily be modified for use in cases where other of the assumptions inherent in the more general treatment are inapplicable. It may, of course, also be used where all the

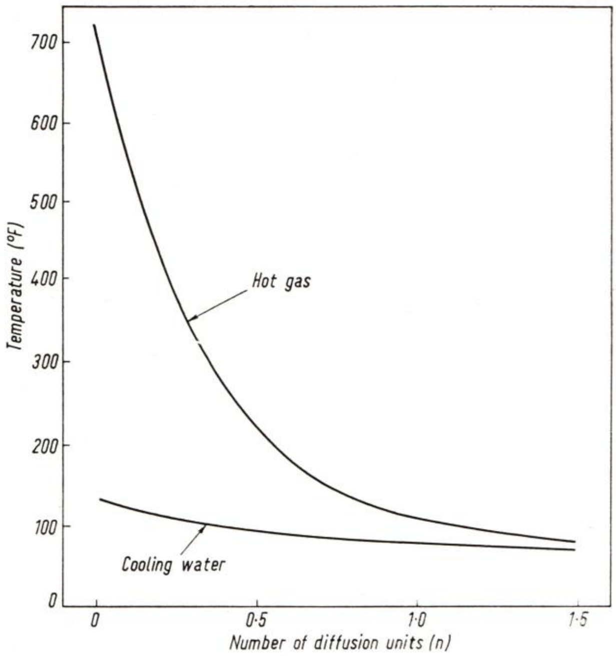


Fig. 1a. Temperature distribution in direct cooler

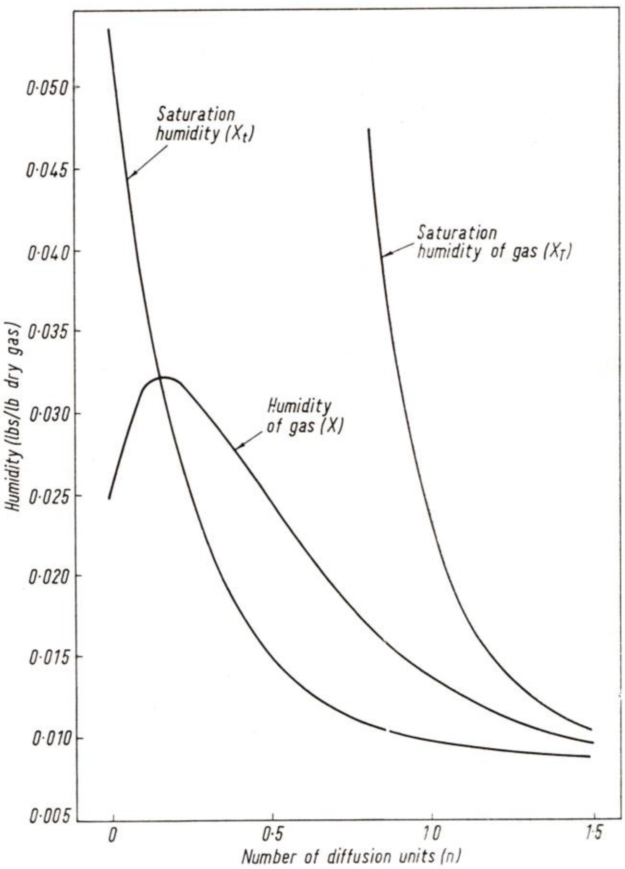


Fig. 1b. Humidity distribution in direct cooler

assumptions apply and has the advantage that the process variables are determined along the length of packed bed since $n \propto Z$ in the general case, when a graphic illustration of what is happening inside the tower is obtained. Because of this it has been found of value when analysing plant-performance tests. For example, reversal in direction of mass transfer is readily illustrated.

It is a trial-and-error method, although, in general, no more than one or two trials are required. The method is time-consuming but is easier to use than it looks and it can be arranged for computation by less-qualified staff.

Two examples have been worked out by Kern's method. Figs. 1*a* and 1*b* show the calculated temperature and humidity distributions, respectively, in a direct cooler designed to cool 270 lb./hr. ft.^{2} of nitrogen at a pressure of 15 p.s.i.g. from 720° to 77°F., with cooling water available at 830 lb./hr. ft.^{2} and at a temperature of 71°F. The water outlet temperature is 131°F. and the dewpoint of the nitrogen, as it leaves the cooler, is 74.6°F., the nitrogen entering the cooler with a moisture content of 0.0246 lb./lb. dry nitrogen. It is possible to obtain this close terminal approach, at this cooling water flow-rate, as long as the gas is not cooled subsequently to below its dewpoint where condensed moisture is of concern. However, Figs. 2*a* and 2*b* illustrate the calculated temperature and humidity distributions, respectively, for a direct cooler designed to cool air at 850 lb./hr. ft.^{2} with cooling water at 580 lb./hr. ft.^{2}, at an operating pressure of 5 p.s.i.g. It is assumed that the air has an inlet temperature of 115°F. and that it contains 0.00775 lb. moisture/lb. dry air. Cooling water is available at 56°F. The direct cooler could have been designed for a duty of 4 diffusion units, but be capable of a load of 8 diffusion units. As illustrated, such over-design would result in outlet gas at about 59°F. which is at least saturated at this temperature. The cooled air is now likely to carry in suspension a fine mist of moisture which may be most difficult to remove.

It can be concluded that a general design method is available which adequately covers the need of the designer. Little is to be gained at present, from the point of view of the designer, by further elaboration of the method. The mean driving force may readily be estimated graphically and Kern's[4] method is known by which more precise calculations may be made when the simplifying assumptions inherent in the more general treatment are inapplicable. There is, however, a lack of correlated data on transfer coefficients.

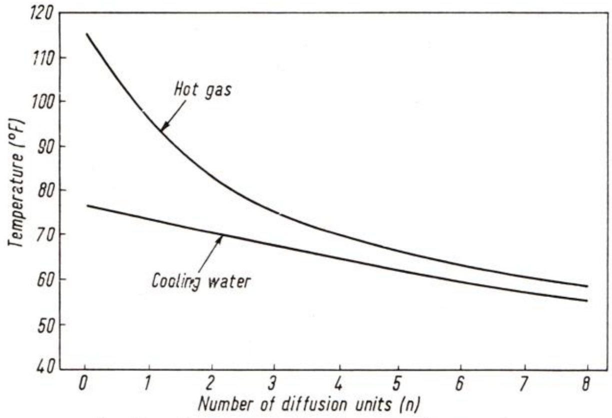


Fig. 2a. Temperature distribution in direct cooler

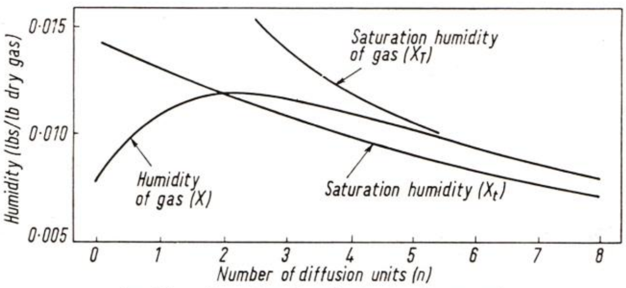


Fig. 2b. Humidity distribution in direct cooler

Effective surface

Uniformity of distribution increases with liquid flow-rate as the differences between one part of the bed and another become a smaller proportion of the mean flow-rate. There is[13] a ' minimum effective liquid rate ' which is the lowest rate at which the packing is effectively wetted. Pratt, when reporting this, stated at the same time that complete wetting of random packings would be unattainable. Different materials, however, differ in the ease with which they are wetted. Mullin[39] finds that the wetting of mild steel depends on its surface condition and that carbon is easily wetted by water.

Leva[34] noticed that as packing size increases so the proportion of the installed area which is wetted effectively decreases. Hollow packing units such as Raschig rings are not wetted to the same degree on their inner and outer surfaces. Hoftyzer and Van Krevelen[30] say that it appears that only a very small part of the inner surface area of Raschig rings is irrigated. Whitt[40] confirmed that flow over Raschig rings is unequally distributed between the inner and outer surfaces and showed how the proportion varied between them with respect to size of ring. Equal gas-flow distribution is probable for rings of size 2 in. and over and equal liquid distribution is probable for rings of small diameter, say about ½-in. size. Whitt considered that the 1-in. size was probably the best alternative, with rings of 1-in. nominal size having the highest wetted surface per cubic foot of packed tower volume.

It is seen that the liquid runs down the solid surface of the packing, which may be only partially and unevenly wetted. The wetted area is less than the installed surface area.[41]

Rate of mass transfer, however, appears to be a direct function of the actual interfacial area,[31] which is much less than the wetted area.[41] Ellis[42] quotes Dankwerts' explanation[43]: even if the packing is thoroughly wetted, there will be areas of stagnant liquid and areas of fast-moving liquid, and it is chiefly where liquid is moving fast that mass transfer by physical absorption occurs. A chemical reaction may render useful those areas where flow is stagnant or slow flowing, but liquid trapped in pockets such as the inside of rings may never become effective.

The interfacial area available for heat transfer appears to be considerably greater than that for mass transfer, as some of the heat from the gas can enter the packing through the dry areas.[32]

The amount of liquid in the packing when liquid is flowing through it is the ' total hold-up '. When the bed is drained, the liquid ultimately left in it is the ' static hold-up '. ' Operating hold-up ' is the difference between total hold-up and static hold-up.[44] Total hold-up depends on liquid flow-rate, but on gas flow-rate only from the loading-point onwards, when the total hold-up increases rapidly with increasing gas flow-rate, indicating that the voids are filling up with liquid. As the gas flow-rate increases further, pressure drop increases rapidly and the tower floods.[45] Packed towers are frequently operated in the loading region[34] where pressure drops are comparatively low and where the packing is fairly well wetted. Operation ' within 70% of flooding ' has been suggested.[46]

Industrial installations, however, operate over a comparatively restricted range of flow conditions and it is considered that laboratory investigations should be supplemented by test data obtained from full-scale installations.

Packing materials and wall-effect

Commonly-used packing materials are stoneware, porcelain, carbon and metals. The smaller sizes of packing units are dumped into the tower, the larger sizes are stacked. When dumped, the packing is homogeneous and the tendency for channeling of the gas and liquid streams is minimised.[32] Random rings are very much more self-distributing than stacked rings.[38] Prefabricated metal-grid and ceramic-tile packings are available, but only dumped packings such as Raschig and Lessing rings are considered here in detail.

The packing units are generally dumped into the tower after this has been filled with water. This avoids breakage of ceramic material and results in a bed of higher voidage than when the packing units are dumped into a dry tower. It is said that wet-filling results in more even liquid flow as it avoids orientation of packing units due to formation of arches. However, such gains are likely to be short-lived. The packing compacts fairly quickly in use so that the advantage of wet-packing over dry-packing is that it reduces breakage of packing units during charging of the tower. Breakage of packing units alters the packing characteristics, resulting in higher pressure drop, some maldistribution and the possibility of an onset of localised flooding earlier than expected.

The wall-effect is the effect of the tower wall on the bulk density of the packing, and this effect has been related to the ratio between the particle diameter and the tower diameter. For example, Leva[34] states that there is a tendency for the liquid to flow towards the wall when (d/D) is greater than 0.143. Sherwood and Pigford[32] cite the work of Baker *et al.*[35] as indicating that reasonably uniform liquid distribution is obtained with either regular or irregular solid packing materials, provided (d/D) is smaller than 0.125. However, Leva[36] also cites the work of Schwartz and Smith[37] as indicating that wall effects may not yet be discounted when (d/D) is smaller than 0.125.

Properties of packed beds

It is characteristic of granular materials that pressure varies with direction. At any particular level in a tower filled with a fluid, lateral and vertical pressures are equal. For a solid, the lateral pressure is zero. The granular material falls between the two cases. There is a lateral pressure but it is not equal to the vertical pressure exerted by the material. The vertical (downward) pressure is greater than the lateral pressure, for a granular material.

Considering, for example, the pressures at the bottom support plate of the tower, both lateral and vertical pressures increase, as the depth of packing is increased, up to a point and then remain constant. Beyond this point any additional packing material is supported by the shell. The lateral pressure exerted by the material transmits a large part of its weight to the tower shell, which thus carries what may in certain circumstances be a heavy load compared with the total pressure, so that it may have to be designed to resist buckling under compression. The ratio between the vertical and lateral forces, which determines the extent to which the material is supported by the shell, is a function of the internal friction of the packing material and of the frictional resistance between the material and the shell. As can be seen from published photographs,[14] the coefficient of internal friction for 1-in. *Intalox* saddles appears to be completely different from that for 1-in. Raschig rings.

In the course of transmitting pressures to the shell, arches are formed by the material, resulting in some orientation of either packing units and/or of points of contact. The extent of arching depends on the dimensions of the shell and on the depth of packing as well as to some extent on the compressibility of the material, where this is compressible. The greater the pressure, the greater is the compaction of the material, the greater is its bulk density and the smaller is its fractional voidage.

When strong arching occurs, the material is carried by the shell almost entirely. At intermediate conditions of arching the material is carried partly by the shell and partly by the bottom support plate, in varying proportions. Where arching is low, almost the whole of the material is carried by the bottom support.

Strong arching means that, in the end, it is not possible to discharge the material through an opening at the bottom of the tower. For a compressible material, this may also compact under low arching to near-solidity, and can again not be discharged. Hence for any granular material the designer may choose a suitable diameter so that sufficient of the load is carried by the shell to prevent compaction whilst avoiding strong arching. The smaller the diameter, the stronger is arching, the greater is the load carried by the wall, the less is the compaction.

As regards Raschig and Lessing rings, it is considered that they are incompressible rather than compressible and strong arching is unlikely to occur in industrial practice, so that diameter of shell is not critical. However, diameter of shell in laboratory-size equipment, because of its small size, may support the packing to the extent of increasing the bed voidage to the point where results are significantly affected by diameter. This may explain the so-called wall-effect. The degree to which liquid tends to migrate to the shell of the equipment, depending as it does on the degree of arching, would then also be a problem which would affect materially results obtained from small-scale but not those from industrial equipment.

Pressure distribution in packed beds

For a perfect granular material, *e.g.* one which is incompressible:

$$k = \frac{P_L}{P_V} = \frac{1 - \sin\phi}{1 + \sin\phi} \quad \text{(12)}$$

For a solid, $\phi = 90°$ and both k and P_L do not exist. For a fluid, $\phi = 0°$ and $P_L = P_V$.

It can be shown[15] that

$$P_V = \frac{\rho R}{k\mu}\left(1 - e^{-k\mu Z/R}\right) \quad \text{(13)}$$

P_L is then also determined, since

$$P_L = k.\,P_V \quad \text{(12a)}$$

We may transform equation (13) to the variables of concern in the design of packed towers, as follows:

$$R = \frac{D}{4} \quad \text{(14)}$$

so that

$$\frac{Z}{R} = 4\left(\frac{Z}{D}\right) \quad \text{(14a)}$$

Table 1

Nominal size, in.	*Angle of repose, φ*
$1\frac{3}{8} \times 1\frac{3}{8} \times (\frac{5}{32})$	36°
$2 \times 2 \times (\frac{13}{64})$	35°
$2\frac{3}{8} \times 2\frac{3}{8} \times (\frac{1}{4})$	40°

Further,

$$\rho = (1 - \varepsilon)\,\rho_p \quad \ldots\ldots\ldots\ldots \quad (15)$$

so that

$$P_V = (1 - \varepsilon)\,\frac{\rho_p .\, D}{4k\mu}\,[1 - e^{-4k\mu(Z/D)}] \quad \ldots\ldots\ldots \quad (13a)$$

Equation (13*a*), in the form in which it is used later on, is:

$$\frac{P_V}{1 - \varepsilon} = \frac{\rho_p .\, D}{4k\mu}\,[1 - e^{-4k\mu(Z/D)}] \quad \ldots\ldots\ldots \quad (13b)$$

Before equation (13*a*) can be used, one requires data on μ and k for different packing materials, and such data are not available. Weinreb and Randall[16] give the sole published data, known to the author, and these apply to Raschig rings only as shown in Table 1.

There is no doubt that the angle of repose varies from one packing material to another and that, in the case of Raschig rings, it is likely to depend on thickness of ring wall. However, thicknesses are not given by Weinreb and Randall and, in the table above, the figures in brackets are assumed as likely. Leva[14] has published photographs which illustrate, qualitatively, the very considerable difference in angle of repose between Raschig rings and *Intalox* saddles.

In the absence of reliable data on μ and k, we cannot use equation (13*a*) effectively. We can, however, compare the free voidage of packing materials with voidages obtained in packed beds for the same material, to see whether the diameter of the tower significantly affects the voidage, irrespective of the size of the packing unit, *i.e.* irrespective of the commonly-used d_p/D ratio.

Free voidage of Raschig and Lessing rings

The free voidage of a packing material is obtained when the material is not restrained by containing walls and when it is under no compacting forces. It might be obtained in a layer of the material about 1 ft. in depth, extending a considerable way in either horizontal direction.

A considerable amount of data on 'free' voidage is published in manufacturers' brochures[16–19] and it is these data which are here analysed. Such data are, however, only approximate and the method by which they are obtained is not stated, although voidages are likely to have been determined by a method such as weighing a box of dimensions $1 \times 1 \times 1$ ft., with and without the packing material, when the voidage may be calculated from the difference in weight and from mean packing dimensions. A voidage determined in this way would not necessarily be the free voidage but merely the best available estimate of it. The free voidage as estimated from manufacturers' data is here denoted by ε'.

One may calculate the density of the actual packing material from the given data. The scatter of the results of such calculations is a measure of the reliability of the data (see Fig. 3). The density does not appear to be affected by manufacturing processes as it is independent of nominal size. There is no significant difference between the data from one manufacturer as compared with another. Bearing in mind the scatter of the results, it is not surprising that no distinction can be made between stoneware and porcelain,

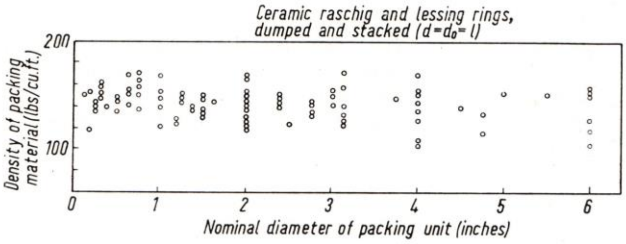


Fig. 3. Reliability of data

the most commonly-used materials. The calculated density of the ceramic material varies between 110 and 170 lb./cu.ft., which compares with the stated densities of 150 lb./cu.ft. (ref. 17) and 152 lb./cu.ft. (ref. 16) for stoneware and 155 lb./cu.ft. (ref. 16) for porcelain. The actual density of the material is unlikely to vary between limits as wide as those found here and it is concluded that manufacturers' data on voidage apply to within $\pm 20\%$ or so, as regards a general correlation. This throws some doubt on correlations in which voidage plays a part and which are not based on a precisely-determined voidage as found in the actual packed bed. The designer as well as the scientist has to allow for this uncertainty in fractional voidage and thus in specific surface area.

Voidage depends also on the wall thickness used. As the thickness tends to zero, the fractional voidage tends to unity, a condition closely realised with mild steel rings (Fig. 4). The data may be correlated as shown in Fig. 4 for a particular size of packing, or as shown in Fig. 5 for a particular wall thickness. Figs. 4 and 5 illustrate the degree of correlation obtained and by plotting and cross-plotting in this way one may obtain the more general correlation given in Fig. 6 which illustrates the effect of both packing size and wall thickness on the fractional voidage ε', for dumped Raschig rings. The effect of wall thickness on voidage is extremely important for the range of packing sizes commonly used and it is therefore of some considerable importance to the scientist and to the designer that wall thickness be determined and specified, respectively. Further, correlations of pressure drop, loading and flooding data, such as that by Eduljee,[20] which depend on the use of a packing factor, are of limited use until the packing factor can be related to the properties of the packed bed as dependent on the dimensions of the packing unit. For example, Eduljee finds it necessary to give two values of packing factor, namely 1.0000 for Raschig rings and 0.6104 for metal Raschig rings.

A more fundamental way of correlating the voidage data on Raschig and Lessing rings is illustrated by Figs. 7 and 8, respectively. The fractional voidage ε' is shown plotted against the ratio d_i/d_o, where d_i and d_o are the internal and external diameter of the packing unit. When the ratio equals unity, then $\varepsilon' = 1$ and when the ratio equals zero, then ε' should be the value appropriate to solid cylinders. This method of correlating the data also has the advantage that all the results contribute to a single curve so that the scatter of the points gives a reliable indication of the limits of accuracy. One would not be far wrong in assuming that the fractional voidage ε' for solid cylinders lies somewhere between 0.37 and 0.43 and hence the lines for both Raschig and Lessing rings have been extrapolated to $\varepsilon' = 0.4$ at $(d_i/d_o) = 0$ in Fig. 9, which compares Raschig with Lessing rings. As the correlations given in Figs. 6 and 9 were obtained from the same basic data, but independent of each other, the curves in Fig. 6 do not compare precisely with that in Fig. 7. The latter is recommended for use as it illustrates the scatter, *i.e.* the limits of reliability.

Voidage of Raschig ring beds

Zhavoronnkov[26] gives data on the voidage of packed beds of ceramic Raschig rings of between $\frac{5}{8}$ and 2 in. nominal diameter, in columns of between $2\frac{1}{2}$ and $17\frac{1}{4}$ in. diam. (These data are recommended by Hobler,[27] who has investigated the design of direct contact equipment in some detail. Zhavoronnkov gives, *inter alia*, data on heat-transfer coefficients, and how they are affected by air and water rates as well as by the degree of wetting.) Pratt *et al.*,[21–25] working on liquid-liquid extraction, have reported voidages of packed beds consisting of Raschig rings in borosilicate glass columns. Data on ceramic rings varying in size from $\frac{1}{4}$ to $1\frac{1}{2}$ in. nominal diameter are given for columns the diameter of which varied between 2 and 12 in.

The effect of the dimensions of the packed bed on its voidage may be measured by the ratio ε/ε' where ε is the actual or measured voidage in the packed bed and where ε' is the free voidage for the packing unit under consideration. Values of ε' are taken from Fig. 7 which applies to dumped rings characterised by $d = d_o = l$. When d_o only approximates to l and also where precise measurements are available, then the nominal diameter is evaluated from $d = \sqrt{ld_o}$. One may then calculate the dimensionless ratios $(\varepsilon/\varepsilon')$ and (d/D) from the given data and by correlating these two ratios with each other attempt to determine how bed dimensions affect bed voidage. Fig. 10 shows the data of Pratt and of Zhavoronnkov plotted in this way. It should be noted that, in the ratio (d/D), d is the nominal diameter of the packing unit, *i.e.* of Raschig rings.

Perry[28] gives a correlation which is said to allow for wall-effect in the calculation of pressure drops. It consists of curves of 'wall-effect factors' against (d_p/D); d_p is said to be the 'particle diameter'. The correlation shows that as the size of the packing unit increases with respect to the bed diameter there is a corresponding reduction in pressure drop. Fig. 10 indicates that the actual voidage in the packed bed increases as the ring size increases with respect to bed diameter, so that pressure drop would be reduced accordingly. To that extent there is agreement between Fig. 10 and Perry's correlation.

The particular correlation given by Perry is taken from the work of Furnas,[29] who investigated beds of broken solids and who defined 'particle diameter' as equivalent spherical diameter, *i.e.* as the diameter of the sphere having the same volume as the mean packing unit. Furnas' wall-effect factor cannot, therefore, be applied to hollow packings such as Raschig rings with confidence but his wall-effect factor disappears as the packing unit becomes very small in

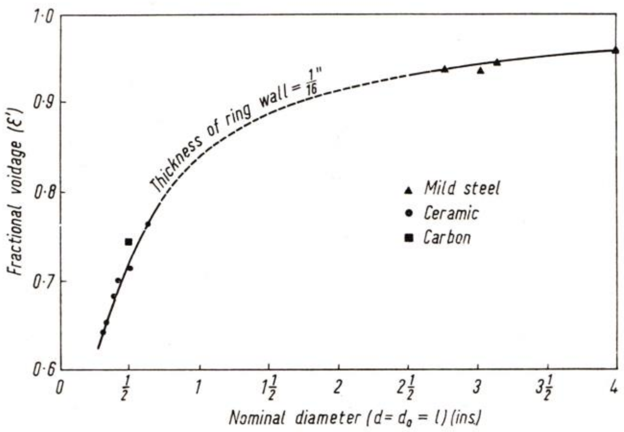


Fig. 5. Free voidage of dumped Raschig rings

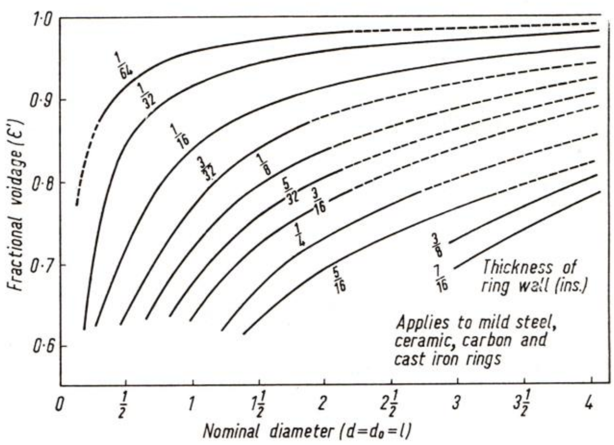


Fig. 6. Free voidage of dumped Raschig rings

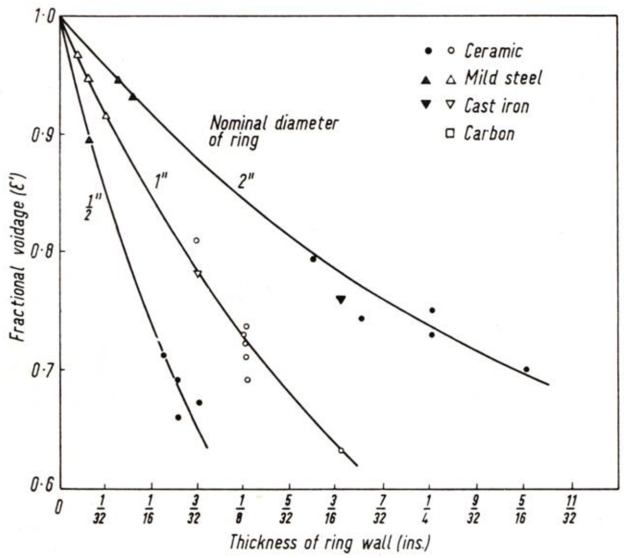


Fig. 4. Free voidage of dumped Raschig rings ($d = d_o = l$)

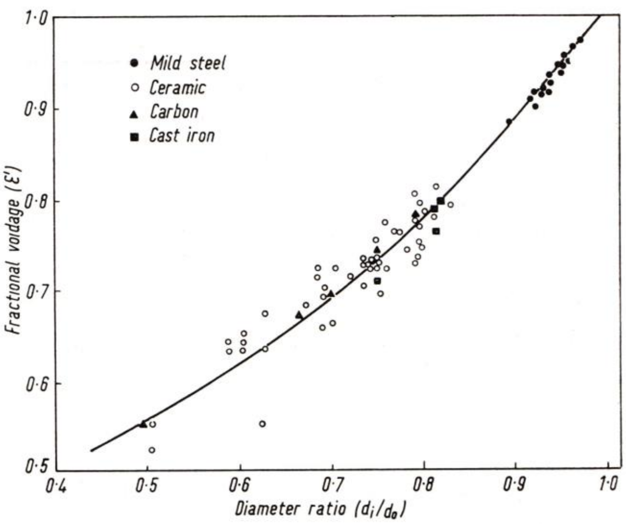


Fig. 7. Free voidage of dumped Raschig rings ($d = d_o = l$)

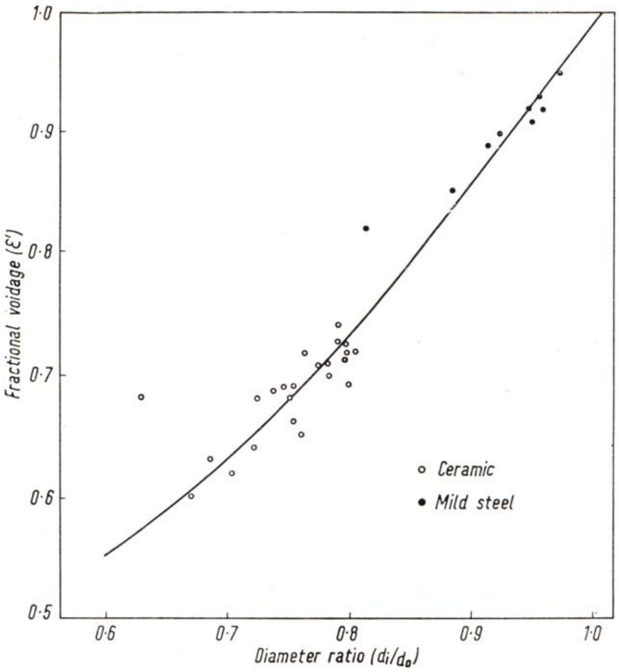


Fig. 8. Free voidage of dumped Lessing rings ($d = d_o = l$)

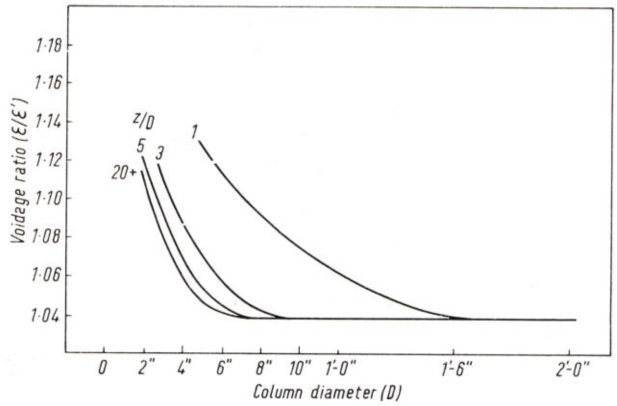


Fig. 12. Predicted voidage of packed beds of dumped ceramic Raschig rings in mild steel columns

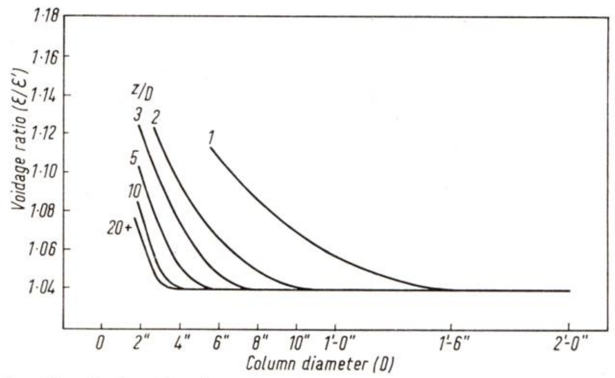


Fig. 13. Predicted voidage of packed beds of dumped ceramic Raschig rings in glass columns

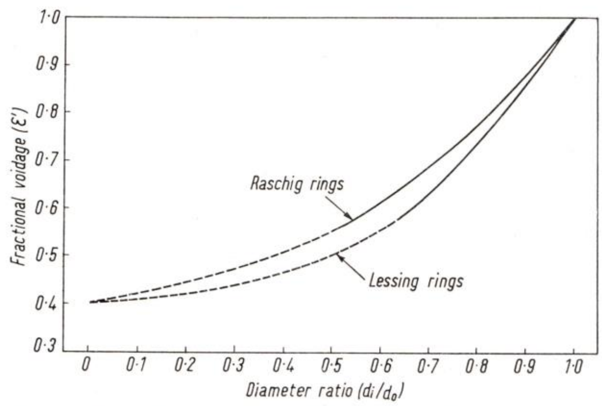


Fig. 9. Free voidage of dumped ceramic, carbon, mild steel and cast iron Raschig and Lessing rings ($d = d_o = l$)

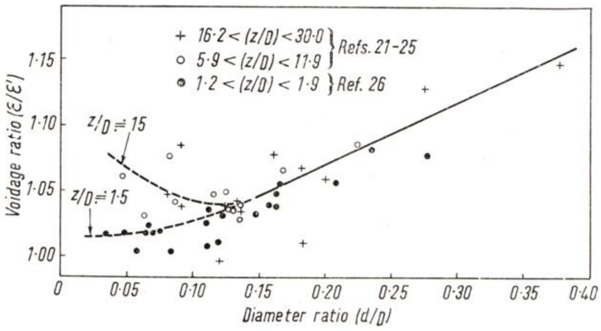
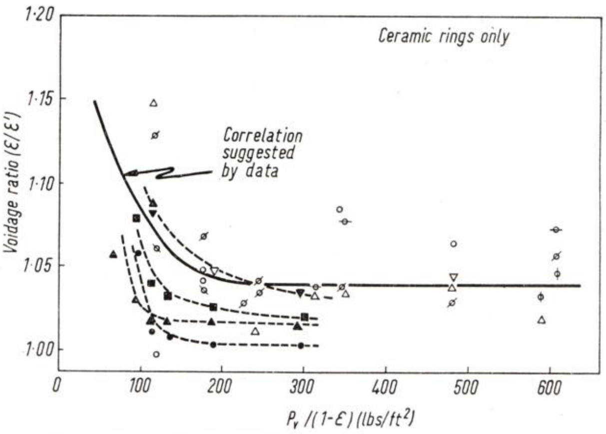


Fig. 10. Voidage of ceramic Raschig rings in packed beds



Author ref.	Symbol	Nominal ring size (ins.)
21–25	○	1/4
	⊗	3/8
	ø	1/2
	△	3/4
	⊖	1
	▽	1
	ɸ	1½
26	▲	5/8
	●	1
	■	1⅜
	▼	2

Fig. 11. Voidage of Raschig rings in packed beds

relation to bed diameter. But it appears from Fig. 10 that the voidage of packed beds, when ratio (d/D) is less than 0.125, may be determined by the depth of the bed rather than by the (d/D) ratio. This is of concern, as most industrial towers operate in the range where (d/D) is equal to or smaller than 0.125. For example, should bed voidage be greater than expected by about 8%, the available surface area would be reduced by about 20%, and the 'packing factor' $(= a/\varepsilon^3)$ by about 35%.

We are comparing data from only two investigators, so that we conclude that it appears, tentatively, as if the depth of packed bed has an effect on fractional voidage of the bed, at those values of the ratio (d/D) which apply to full-scale equipment.

The ratio (d/D) is an empirical variable which has been found in the past to correlate data such as, for example, data on pressure drop. Different investigators appear to have interpreted d differently in an effort to reduce the experimental scatter in the resulting correlation. Hence a different, but more fundamental, method of correlation may be used, based on the analysis given earlier on the properties of packed beds and on the pressure distribution in such beds. We can calculate $P_V/(1-\varepsilon)$ from the experimental data using equation (13*b*), and correlate this with the ratio $(\varepsilon/\varepsilon')$. Plotting $P_V/(1-\varepsilon)$ against $(\varepsilon/\varepsilon')$ should yield a stress-strain diagram for the packing in its dumped form, in convenient form for use with equation (13*b*).

The basic data for use with equation (13*b*) are not available so that this equation cannot be used effectively. However, we can make certain assumptions such as:

(1) $\phi = 35°$, so that $k = 0.270$. In the absence of more precise data it is assumed that the same values of k and ϕ apply to Raschig rings of all sizes.

(2) $\mu = 0.20$ for ceramic materials on glass. It is assumed, in the absence of more precise data, that μ is constant with respect to ring size and wall thickness so that it depends only on the particular combination of ring material and tower material. It is further assumed that Zhavoronnkov used equipment constructed of glass.

(3) $\rho_p = 152$ lb./cu.ft.

The resulting correlation is given in Fig. 11. As regards scatter of results, it is not much better than that in Fig. 10, but it shows that the dumped packing compacts as pressure increases, up to a point beyond which no further compaction occurs, the voidage of the bed remaining constant as pressure increases. Bearing in mind the limitation set by the limits of accuracy with which ε' was correlated above with the packing dimensions, and the assumptions made, it is not surprising that the data of Zhavoronnkov form separate curves, of similar shape, for different ring sizes, and that his data are about 2% lower than those of Pratt.

A curve may be drawn through the data (see Fig. 11) which may be taken as giving at least some indication of the $P_V/(1-\varepsilon)$ versus ε/ε' relationship for ceramic Raschig rings. This may be used to predict the effect of the dimensions of packed beds on bed voidage, by calculating $P_V/(1-\varepsilon)$ from equation (13*b*), and then finding ε/ε' from Fig. 11. Such calculations have been made and are illustrated by Figs. 12 and 13, for ceramic Raschig rings in mild steel and in glass towers, respectively. In deriving Fig. 12, the coefficient of friction μ for ceramic Raschig rings, of all sizes, on mild steel was assumed to be 0.35.

Figs. 12 and 13 indicate that the voidage in a packed bed in full-size equipment is perhaps 4% greater than the free voidage, but that it is independent of the dimensions of the bed. The voidage of packed beds of laboratory-size equipment, although this is made of glass, is very considerably affected by the dimensions of the packed bed. The data do not cover full-scale equipment and it is possible that the packing may compact further as tower diameter increases.

The argument and conclusions may be summarised by saying that the wall-effect is caused by the bed dimensions affecting the properties of the packed bed. A consideration of the properties of packed beds leads to the hypothesis that it is the pressure distribution in the packed bed which affects the voidage. The correlation which results from this hypothesis correlates the voidage data as well as a more conventional correlation in terms of the ratio (particle diameter/bed diameter), bearing in mind the assumptions which had to be made, and appears to have a more fundamental basis. Whereas the more conventional correlation indicates that 'wall-effects' are likely to be a factor in industrial full-scale equipment, the hypothesis here put forward indicates that 'wall-effects' may not matter in full-scale equipment but that they are a matter of concern when working with laboratory-size equipment.

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