Interfacial area for packed towers

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Received on September 28, 1978; Revised on December 24, 1978

Abstract

A model for predicting the values of interfacial area from liquid hold-up is presented for various sizes and shapes of packings generally employed in laboratories and industry. The value of the liquid hold-up has been evaluated from the vertical surface model and random angle model proposed by Davidson. The calculated values are in good agreement with the reported values of wetted area and interfacial area (maximum value) obtained by the chemical method. It is observed that with the increase in size of the packing, the packing behaves as a vertical surface. The reported values of interfacial area for physical absorption and evaporation are also compared with the calculated values.

Key words: Liquid hold-up, packed columns, packings, interfacial area, mass transfer, absorption.

1. Introduction

Design of mass transfer equipment and the prediction of rates of absorption into reacting solutions require the knowledge of mass transfer coefficients of individual phases and the interfacial area.

Experimental data on the performance of absorption towers are usually reported as volumetric mass transfer coefficients (k_La or k_Ga). The volumetric coefficients can be easily determined by physical absorption measurements. Separation of these volumetric coefficients into 'k_L' or 'k_G' and 'a' requires the knowledge of either individual mass transfer coefficient (k_L or k_G) or specific interfacial area.

Several investigators visualized the interfacial area of the liquid in a packed tower to consist of the surfaces of both rapidly moving streams and quiescent accumulations. The thickness and the speed of the liquid layer will also vary from point to point. In the case of physical absorption, the effective interfacial area is that of the rapidly moving liquid, since the thin and slow moving parts of the liquid layer will become saturated with dissolved gas. These parts of the surface may contribute little to interfacial area for physical absorption. On the other hand, in evaporation experiments all parts of the liquid surface will be effective. Thus, the effective interfacial area for evaporation

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will be more than that for physical absorption (Yoshida and Koyanagi[1]). Shulman *et al*[2] discussed the absorption experiments of ammonia into water and solutions of sulfuric acid. It was observed that the value of interfacial area obtained (from $k_G a$ measurements) increased with acid concentration tending to a constant value when the concentration of the acid reached a value of 2 M. This is an indication of difference in interfacial area effective for physical absorption and absorption accompanied by chemical reaction. Joosten and Danckwerts[4] and Patwardhan[6] discussed the differences in interfacial area for physical absorption and absorption with chemical reaction.

Davidson[3] observed that the values of interfacial area are much less than the wetted areas, the difference being much more marked in the case of smaller rings. Also, surface tension forces are able to retain comparatively large volumes of water between the rings, thereby filling up the pore space, and wetting the solid surface without exposing much interface. It is also possible that with the smaller rings there are stagnant pockets of gas within the packing, so that some of the liquid surface is not accessible to the gas flowing through the tower. Onda *et al*[5] have shown that the values of wetted area a_w are equal to the values of interfacial area obtained by absorbing CO_2 into solutions of NaOH.

A model has been presented here to evaluate the interfacial area for mass transfer operation in packed towers from liquid hold-up for four different types of packing (Raschig rings, Berl saddles, Pall rings and Intalox saddles).

2. Hold-up

The liquid hold-up is an important characteristic of packing owing to its relation to the wetted area, pressure drop and flooding characteristics. Fumas and Bellinger[7], Jesser and Elgin[8] showed that the hold-up varied from 0·94 to 0·74 power of liquid rate. Shulman *et al*[2] measured the total hold-up by weighing the column packing while liquid flow was maintained. The operating hold-up was obtained by deducting the static hold-up. The static hold-up was measured as the weight of liquid retained when the column had drained to a constant weight. Shulman *et al*[2] observed that the operating hold-up is independent of the nature of the packing surface, whereas the static hold-up may vary with the porosity of the material of the packing. Broz and Kolar[9] observed that for low liquid flow rates the hold-up is almost constant and increases only near the flooding, and gas flow rate has little effect. Mohanta and Laddha[10] proposed a correlation for operating hold-up based on the velocity of liquid (based on empty column) and the number of pieces per cubic foot. Otake and Okada[11] proposed dimensionless correlation for operating hold-up in a bed of Raschig rings and Berl saddles. Varrier and Rao[12] correlation appears to be a modification of Otake and Okada[11] correlation.

Davidson[3] obtained a correlation based on theoretical considerations. These investigations showed that the hold-up depends mainly on the size of the packing. But static hold-up is more on the smaller packings owing to the quantity of liquid held by capillary forces at the points of contact of the packing and these points of contact will be more for smaller size packings.

3. Development of the model

In an absorption tower liquid usually flows as a film over the surface of a solid packing and exposes a large area for absorption. The thickness and velocity of the film are normally such that the flow is streamlined. For laminar flow over a vertical plate, the velocity profile is given as[13]

$$V_z = \frac{\rho g}{2\mu}(m^2 - x^2) \tag{1}$$

where 'm' is the film thickness.

The maximum velocity exists at a point farthest from the wall (at $x = 0$) is given by

$$V_{z\,\max} = \frac{\rho g m^2}{2\mu}. \tag{2}$$

The average volumetric flow rate of liquid (Q) is given by

$$Q = \int_0^w \int_0^m V_{z\,\text{avg}}\, dx\, dy = V_{z\,\text{avg}} \int_0^w \int_0^m dx\, dy = wm\, V_{z\,\text{avg}} \tag{3}$$

where w = width of the film.

Average velocity, $V_{z\,\text{avg}} = \dfrac{\text{Total flow rate}}{\text{Total cross-sectional area}}$

$$= \frac{\int_0^w \int_0^m V_z\, dx\, dy}{\int_0^w \int_0^m dx\, dy} = \frac{\int_0^w \int_0^m V_z\, dx\, dy}{wm}. \tag{4}$$

In eqn. (4), V_z is a function only of x and not of y. Therefore

$$V_{z\,\text{avg}} = \frac{w \int_0^m V_z\, dx}{wm} = \frac{\int_0^m V_z\, dx}{m} \tag{5}$$

Expressing V_z in terms of x

$$(V_z)_{\text{avg}} = \frac{\int_0^m \frac{\rho g}{2\mu}(m^2 - x^2)\, dx}{m}$$

$$= \frac{\rho g m^3}{3\mu m} = \frac{\rho g m^2}{3\mu}. \tag{6}$$

Substituting the value of $(V_e)_{avg}$ from eqn. (6) into eqn. (3), the volumetric flow rate,

$$Q = \frac{\rho g m^2}{3\mu} \, wm = \frac{\rho g w m^3}{3\mu}. \tag{7}$$

From eqn. (7), film thickness, 'm', is given by

$$m = \left(\frac{3\mu Q}{\rho g w}\right)^{1/3}.$$

Hence for a given mass flow rate $L_m = aQ\rho/w$, the film thickness

$$m = \left[\frac{3\mu L_m}{a\rho^2 g}\right]^{1/3} \tag{8}$$

where a = surface area per unit volume cm^2/cm^3 and L_m = mass flow rate g/cm^2 sec. The Reynolds number for vertical surfaces is given by

$$\text{Re}_1 = 4L_m/a\mu.$$

The Grashof number, $\text{Gr} = gd^3/\nu^2$. Eqn. (8) can be written in terms of Re_1 and Gr, as

$$m = \left(\frac{3}{4}\frac{\text{Re}_1}{\text{Gr}} \cdot d^3\right)^{1/3}$$

$$= 0 \cdot 909\, d\left(\frac{\text{Re}_1}{\text{Gr}}\right)^{1/3} \tag{9}$$

where 'd' is the characteristic length of the packing. It is assumed that the solid packings are made up of large number of either vertical surfaces of height 'd', or consisting of a large number of surfaces inclined at an angle to the horizontal and each of length 'd', adequately and equally wetted by the liquid.

A method of prediction of interfacial area from Davidson's vertical surface (VS) model and random angle (RA) model is presented here. Davidson predicted the hold-up of liquid using Higbie's assumptions[16]. In the vertical surface model, the packing is assumed to consist of a number of vertical surfaces of height 'd' (characteristic length of the packing) whereas in the random angle model, the packing is assumed to consist of a number of inclined surfaces, each of length 'd', the inclination to horizontal being random.

The mean film thickness 'm' in terms of operating liquid hold-up 'h' (total volume of liquid within unit volume of tower) was given by Davidson as:

$$\frac{m}{d} = \frac{h}{ad}. \tag{10}$$

Combining eqns. (9) and (10), the hold-up for the vertical surface model is given by:

$$h_{VS} = 0 \cdot 909\, ad\, [\text{Re}_1/\text{Gr}]^{1/3}. \tag{11}$$

Substituting for Re_1 and Gr, eqn. (11) becomes

$$h_{VS} = 0 \cdot 145\, [L_m \mu a^2/\rho^2]^{1/3} \tag{12}$$

where

$$g = \text{cm/sec}^2.$$

Similarly, the hold-up from Davidson's random angle model is given by

$$h_{RA} = 1 \cdot 217\, ad\, (\text{Re}/\text{Gr})^{1/3} \tag{13}$$

where Re is the Reynolds number for random packing

$$= 2\pi L_m/a\mu.$$

Substituting for Re and Gr in eqn. (13),

$$h_{RA} = 0 \cdot 226\, [L_m\, \mu a^2/\rho^2]^{1/3}. \tag{14}$$

From the definition of hold-up, h (volume of liquid held per unit volume of packing) and the voidage, ϵ (free space available for gas and liquid per unit volume of packing) the volume occupied by the liquid per unit volume of tower is

$$V_{VS} = h_{VS}/\epsilon \tag{15}$$

$$V_{RA} = h_{RA}/\epsilon \tag{16}$$

In packed towers considerable amount of liquid is in the form of liquid held between packings (particularly in smaller size packings) and in the form of thin films, which do not contribute significantly to mass transfer in the case of physical absorption. This may be due to the fact that thin and slow moving films get saturated. However, these will be contributing to mass transfer in evaporation and absorption with chemical reaction due to the absence of concentration gradients in the liquid phase. Thus, the interfacial area effective for evaporation and for absorption with chemical reaction will be more than that of the physical absorption alone. The interfacial area obtained by chemical method refers to the maximum value which is independent of reactant concentration.

An attempt has been made to evaluate the effective interfacial area available for evaporation and absorption with chemical reaction as follows : The interfacial area is assumed to be the surface area of a sphere occupying the volume of liquid hold-up (V_{VS} and V_{RA}). Thus if the total liquid is 'V' then the surface area is evaluated as:

$$V = \frac{4}{3} \pi r^3 \tag{17}$$

$$r = (3V/4\pi)^{1/3}. \tag{18}$$

The surface area of the sphere

$$SA = 4\pi r^2. \tag{19}$$

Substituting for 'r' from eqn. (18)

$$SA = 4\pi (3V/4\pi)^{2/3}$$
$$= 4 \cdot 8387 \, (V)^{2/3}. \tag{20}$$

The interfacial area is evaluated for various packings from the volume of liquid hold-up. Though the wetted area range from 20–80% of the total surface area, the effective interfacial area could be much less because of the liquid hold-up in the packings. As the hold-up varies with the size of the packing (d) an attempt has been made to account for the extra contribution to interfacial area due to reaction considering the size of the packing. From the data collected this extra contribution to interfacial area (a_S) is estimated, taking into account the size of the packing. Comparing the value of SA with the literature data on wetted area and interfacial area for absorption with chemical reaction it was found that the area in excess of SA could be empirically related to the nominal size of the packing (d) as:

$$a_S = \frac{0 \cdot 5}{d}. \tag{21}$$

The effective interfacial area for physical absorption based on vertical surface model hold-up volume from eqn. (20) is

$$IA_{VS} = 4 \cdot 8387 \, (V_{VS})^{2/3} \tag{22}$$

and that based on random angle model is

$$IA_{RA} = 4 \cdot 8387 \, (V_{RA})^{2/3}. \tag{23}$$

The effective interfacial area for absorption with chemical reaction and evaporation based on vertical surface model hold-up volume and that based on random angle model from eqns. (20) and (21) can be written as

$$IA_{VS} = 4 \cdot 8387 \, (V_{VS})^{2/3} + (0 \cdot 5/d) \tag{24}$$

$$IA_{RA} = 4 \cdot 8387 \, (V_{RA})^{2/3} + (0 \cdot 5/d). \tag{25}$$

4. Results and discussion

For four types of packings, *viz.*, Raschig rings, Berl saddles, Pall rings and Intalox saddles, the values of interfacial area from eqns. (22), (23), (24) and (25) have been calculated. The geometric surface area of the packing is calculated from the shape factor '$a_t D_P$' given by Onda *et al*[14]. These values are given in Table I, along with the values of voidage (ϵ). The physical properties for water have been used in all the calculations as most of the properties of solutions lie in the same region.

Table I

Values of Voidage (ϵ) and shape factor ($a_t D_p$)

Packing	Shape factor $a_t D_p$	Voidage (ϵ) for sizes (cm) 1·27	2·54	3·81	5·08	7·62	10·16
Raschig rings	4·7	0·64	0·73	0·68	0·74	0·74	..
Berl saddles	5·6	0·65	0·69	0·72	..	..	..
Pall rings	5·8	..	0·73	0·76	0·78	..	0·82
Intalox saddles	7·1	0·78	0·77	0·80	0·79	..	..

5. Effective interfacial area for evaporation and absorption with chemical reaction

The values of effective interfacial area from eqns. (24) and (25) based on vertical surface model (IA_{VS}) and random angle model (IA_{RA}) for absorption with chemical reaction and evaporation are given in Tables II to V.

The wetted surface area (a_w) of the packing is calculated from Onda's equation[5] :

$$\frac{a_W}{a_t} = 1 - \exp\left[- 1\cdot45\,(\sigma c/\sigma)^{0\cdot75}\left(\frac{L}{a_t\,M_L}\right)^{0.1}\,(L^2\,a_t/\rho^2\,g)^{-0\cdot05}\,(L^2/\rho\sigma a_t)^{0\cdot2}\right]. \tag{26}$$

The wetted areas calculated from this equation for various shapes and sizes of packing are given in Tables II to V. They include the values of effective interfacial area calculated from eqns. (24) and (25) and the values of interfacial area for the absorption of carbon dioxide in the temperature range 20–25° C. Eqn. (26) is applicable within $\pm$ 20% error for 'a_w' to the column packed with Raschig rings, Berl saddles, ceramic spheres, glass and polyvinyl chloride spheres.

5.1. *Raschig rings*

Table II indicates that the values of interfacial area calculated by the use of vertical surface model are in good agreement with the calculated values of wetted area (Onda *et al*[5]) and values of interfacial area reported by Danckwerts and Sharma[15] up to the superficial liquid flow rate of 0·2 cm/sec. Above this superficial flow rate, the calculated values of interfacial area by random angle model [eqn. (25)] are in good agreement with those values of wetted area (Onda *et al*[5]) and interfacial area (Danckwerts[15]) for 1·27 and 2·54 cm Raschig rings.

From Table II it can be seen that the values of interfacial area calculated based on vertical surface model [eqn (24)] are in good agreement with those values of wetted area (Onda *et al*[5]). These values are also reasonably satisfactory compared to those reported by Danckwerts and Sharma for 3·81 cm Raschig rings. It can also be observed that with increase in size of the Raschig rings, the packing behaves as a vertical surface.

5.2. *Berl saddles*

From Table III it is evident that values of interfacial area for 1·27 cm and 2·54 cm Berl saddles are in good agreement with those predicted from eqn. (26) (for wetted area). The above values are in close agreement with those reported by Onda *et al*[5] for CO_2–NaOH system. The values of wetted area presented in Table III for 3·81 cm Berl saddles are in good agreement with the values calculated from vertical surface model.

5.3. *Pall rings*

Table IV indicates that the values of interfacial area calculated from vertical surface model agree reasonably well with the wetted areas [eqn. (26)] up to a superficial liquid flow rate of 0·2 cm/sec. Beyond this superficial liquid flow rate, the values are in agreement with those predicted by random angle model for 2·54 cm and 3·81 cm Pall rings. However, the values of interfacial area by chemical method[15] are higher compared to the values of interfacial area calculated by random angle model. This may be due to the complex geometry of the Pall rings which may influence the liquid flow and the mixing characteristics.

The values of interfacial area from vertical surface model are in good agreement with the values of wetted area [calculated from eqn. (26)] for 5·08 and 10·16 cm Pall rings (Table IV).

5.4. *Intalox saddles*

In the case of Intalox saddles, the values of interfacial area calculated from random angle model for 1·27 cm and 2·54 cm sizes are lower than the values of wetted area [eqn. (26)] and interfacial area reported by Danckwerts and Sharma[15]. However, for sizes 3·81 cm ard 5·04 cm, the values of interfacial area calculated by vertical surface model with 0·15 cm/sec and 0·2 cm/sec superficial liquid flow rates respectively are in good agreement with the values of wetted area [eqn. (26)]. Above this superficial

Table II

Effective interfacial area of columns with Raschig rings (cm^2/cm^3)

Superficial liquid flow rate, L cm/sec	Interfacial area cm^2/cm^3			Wetted area cm^2/cm^3 eqn. (26)	% deviations from columns		
	Vertical surface model eqn. (24)	Random angle model eqn. (25)	Danckwerts and Sharma[15]		2 & 5	3 & 5	3 & 4
Size 1·27 cm							
0·05	0·9942	1·1989		0·75	24·56	37·44	
0·10	1·0924	1·3319		1·00	8·46	24·92	
0·15	1·1587	1·4200		1·13	2·48	20·42	
0·20	1·2090	1·4873	1·15	1·22	− 0·91	17·97	22·68
0·40	1·3440	1·6682	1·54	1·54	−14·58	7·68	7·68
0·60	1·4326	1·7877	1·81	1·73	−20·76	3·23	− 1·25
0·80	1·4684	1·8802	2·00	1·88	−28·03	0·00	− 6·37
1·00	1·5575	1·9547	2·09	2·00	−28·42	1·95	− 6·92
Size 2·54 cm							
0·05	0·6437	0·7376		0·51	20·77	30·86	
0·10	0·6665	0·8271		0·62	6·98	25·04	
0·15	0·7105	0·8866		0·70	1·48	21·04	
0·20	0·7444	0·9490	0·72	0·76	− 2·10	19·92	24·13
0·40	0·8358	1·0536	1·00	0·92	−10·07	12·68	5·09
0·60	0·8953	1·1344	1·18	1·02	−13·93	11·22	− 4·02
0·80	0·9413	1·1960	1·28	1·10	−16·86	8·03	− 7·02
1·00	0·9790	1·2466	1·35	1·17	−19·51	6·14	− 8·29
Size 3·81 cm							
0·05	0·4831	0·6036		0·37	23·41	38·70	

Table II (*contd.*)

Superficial liquid flow rate, L cm/sec	Interfacial area cm²/cm³			Wetted area cm²/cm³ eqn. (26)	% deviation from columns		
	Vertical surface model eqn. (24)	Random angle model eqn. (25)	Danckwerts and Sharma[15]		2 & 5	3 & 5	3 & 4
Size 3·81 cm							
0·10	0·5414	0·6817		0·46	15·04	32·52	
0·15	0·5801	0·7340		0·52	10·36	29·16	
0·20	0·6102	0·7736	0·37	0·57	6·59	26·32	52·17
0·40	0·6895	0·8806	0·60	0·68	1·38	22·78	31·86
0·60	0·7422	0·9507	0·77	0·76	− 2·40	20·06	19·01
0·80	0·7824	1·0112	0·93	0·81	− 3·53	19·90	8·03
1·00	0·8148	1·0490	1·04	0·85	− 4·32	18·97	0·86
Size 5·08 cm							
0·05	0·3913	0·4914		0·29	25·89	40·98	
0·10	0·4398	0·5467		0·37	15·87	32·32	
0·15	0·4716	0·5995		0·42	10·94	29·93	
0·20	0·4962	0·6327		0·45	9·31	28·88	
0·40	0·5624	0·7218		0·54	3·98	25·19	
0·60	0·6061	0·7803		0·60	1·00	23·11	
0·80	0·6390	0·8248		0·63	1·05	23·62	
1·00	0·6666	0·8621		0·66	1·00	23·44	
Size 7·62 cm							
0·05	0·3098	0·3937		0·22	28·99	44·12	
0·10	0·3504	0·4479		0·27	22·95	39·72	
0·15	0·3642	0·4839		0·31	14·88	35·94	
0·20	0·2977	0·5427		0·34	14·51	37·35	
0·40	0·4528	0·5859		0·41	9·45	30·02	
0·60	0·4893	0·6348		0·44	10·08	30·69	
0·80	0·5173	0·6720		0·46	11·08	31·55	
1·00	0·5399	0·7030		0·47	12·95	33·14	

Table III

Effective interfacial area with Berl saddles (cm^2/cm^3)

Superficial liquid flow rate, L cm/sec	Interfacial area cm^2/cm^3		Wetted area cm^2/cm^3 eqn. (26)	% deviation from columns	
	Vertical surface model eqn. (24)	Random angle model eqn. (25)		2 & 4	3 & 4
Size 1·27 cm					
0·05	1·06	1·29	0·88	16·98	31·78
0·10	1·15	1·42	1·11	3·48	21·83
0·15	1·21	1·50	1·26	− 4·13	16·00
0·20	1·27	1·56	1·38	− 8·66	11·54
0·40	1·40	1·75	1·77	−26·43	− 1·14
0·60	1·50	1·88	1·99	−32·67	− 5·85
0·80	1·58	1·99	2·16	−36·71	− 8·54
1·00	1·65	2·09	2·29	−38·79	− 9·57
Size 2·54 cm					
0·05	0·64	0·80	0·57	10·94	28·75
0·10	0·72	0·90	0·69	4·17	23·33
0·15	0·77	0·96	0·77	0·00	19·79
0·20	0·81	1·01	0·84	− 3·70	16·83
0·40	0·92	1·15	1·03	−11·96	10·43
0·60	0·99	1·24	1·15	−16·16	7·26
0·80	1·04	1·32	1·25	−20·11	5·30
1·00	1·07	1·38	1·33	−24·30	3·62
Size 3·81 cm					
0·05	0·50	0·62	0·41	18·00	33·87
0·10	0·56	0·71	0·51	8·93	28·17
0·15	0·60	0·76	0·58	3·33	23·68
0·20	0·63	0·80	0·63	0·00	21·25
0·40	0·71	0·91	0·76	− 7·94	16·48
0·60	0·77	0·98	0·84	− 9·09	14·29
0·80	0·81	1·04	0·89	− 9·88	14·42
1·00	0·84	1·09	0·93	−10·71	14·68

Table IV

Effective interfacial area with Pall rings (cm^2/cm^3)

Superficial liquid flow rate, L cm/sec	Interfacial area cm^2/cm^3			Wetted area cm^2/cm^3 eqn. (26)	% deviation from columns		
	Vertical surface model eqn. (24)	Random angle model eqn. (25)	Danckwerts and Sharma[15]		2 & 5	3 & 5	3 & 4
Size 2·54 cm							
0·05	0·6397	0·7903		0·55	14·02	30·41	
0·10	0·7124	0·8885		0·70	1·74	21·22	
0·15	0·7603	0·9539		0·80	− 5·22	16·13	
0·20	0·7976	1·0032	1·24	0·87	− 9·08	13·28	−23·60
0·40	0·8982	1·1368	1·61	1·08	−20·24	5·00	−41·63
0·60	0·9631	1·2253	1·81	1·21	−25·64	1·25	−47·72
0·80	1·0134	1·2935	1·92	1·30	−28·28	− 0·50	−48·43
1·00	1·0545	1·3487	1·96	1·37	−29·92	− 1·58	−45·33
Size 3·81 cm							
0·05	0·4903	0·6132		0·44	10·26	28·25	
0·10	0·5496	0·7062		0·53	3·57	24·95	
0·15	0·5892	0·7549		0·59	− 0·14	20·90	
0·20	0·6191	0·7865		0·65	− 4·99	17·36	
0·40	0·7000	0·8949		0·80	−14·29	10·60	
0·60	0·7531	0·9670		0·89	−18·18	7·96	
0·80	0·7948	1·0222		0·95	−19·53	7·06	
1·00	0·8277	1·0672		0·99	−19·61	7·23	

Table IV (*contd.*)

Superficial liquid flow rate, L cm/sec	Interfacial area cm^2/cm^3			Wetted area cm^2/cm^3 eq. (26)	% deviation from columns		
	Vertical surface model eqn. (24)	Random angle model eqn. (25)	Danckwerts and Sharma[15]		2 & 5	3 & 5	3 & 4
Size 5·08 cm							
0·05	0·4086	0·5152		0·35	14·34	32·07	
0·10	0·4602	0·5844		0·42	8·74	28·13	
0·15	0·4943	0·6298		0·47	4·92	25·37	
0·20	0·5208	0·6652		0·52	0·15	21·83	
0·40	0·5902	0·7585		0·63	− 6·74	16·95	
0·60	0·6366	0·8210		0·71	−11·53	13·52	
0·80	0·6715	0·8689		0·76	−13·18	12·53	
1·00	0·7010	0·9076		0·80	−14·12	11·86	
Size 10·16 cm							
0·05	0·2695	0·3451		0·21	22·08	39·15	
0·10	0·3060	0·3944		0·26	15·03	34·08	
0·15	0·3303	0·4267		0·29	12·20	32·04	
0·20	0·3487	0·4514		0·31	11·10	31·32	
0·40	0·3983	0·5184		0·37	7·11	28·63	
0·60	0·4312	0·5624		0·40	7·24	28·88	
0·80	0·4570	0·5963		0·425	7·00	28·73	
1·00	0·4770	0·6244		0·44	7·76	29·53	

liquid flow rate, the values of wetted area are in agreement with those values (Table V) calculated from random angle model [eqn. (25)].

In this type of packing, the lower value of interfacial area could be explained due to complexity of the geometry of the packing as in the case of Pall rings.

Table V

Effective interfacial area with Intalox saddles (cm^2/cm^3)

Superficial liquid flow rate, L cm/sec	Interfacial area cm^2/cm^3			Wetted area cm^2/cm^3 eqn. (26)	% deviation from columns		
	Vertical surface model eqn. (24)	Random angle model eqn. (25)	Danckwerts and Sharma[15]		2 & 5	3 & 5	3 & 4
Size 1·27 cm							
0·05	1·0256	1·2410		1·00	2·50	19·42	
0·10	1·1297	1·3808		1·33	−17·73	3·68	
0·15	1·1984	1·4737		1·53	−27·67	− 3·82	
0·20	1·2511	1·5439	1·52	1·68	−34·28	− 8·82	1·55
0·40	1·3924	1·7345	2·23	2·06	−47·95	−18·77	−28·57
0·60	1·4868	1·8604	2·74	2·34	−57·38	−25·78	−47·28
0·80	1·5584	1·9561	3·17	2·56	−64·27	−30·87	−62·06
1·00	1·6169	2·0355	3·53	2·74	−69·46	−34·61	−73·42
Size 2·54 cm							
0·05	0·6616	0·8203		0·64	3·26	21·98	
0·10	0·7385	0·9239		0·80	− 8·33	13·41	
0·15	0·7889	0·9921		0·90	−14·08	9·28	
0·20	0·8281	1·0444	0·88	0·99	−19·55	5·21	15·74
0·40	0·9331	1·1847	1·20	1·24	−32·89	− 4·67	− 1·29
0·60	1·0018	1·2776	1·44	1·40	−39·75	− 9·58	−12·71
0·80	1·0545	1·3487	1·65	1·52	−44·14	−12·70	−22·34
1·00	1·0981	1·4073	1·88	1·62	−47·53	−15·11	−33·59

Table V (*contd.*)

Superficial liquid flow rate, L cm/sec	Interfacial area cm²/cm³			Wetted area cm²/cm³ eqn. (26)	% deviation from columns		
	Vertical surface model eqn. (24)	Random angle model eqn. (25)	Danckwerts and Sharma[15]		2 & 5	3 & 5	3 & 4
Size 3·81 cm							
0·05	0·5108	0·6409		0·48	6·03	25·11	
0·10	0·5737	0·7251		0·60	− 4·58	17·25	
0·15	0·6152	0·7812		0·68	−10·53	12·95	
0·20	0·6467	0·8238		0·76	−17·52	7·74	
0·40	0·7328	0·9389		0·94	−28·28	− 0·12	
0·60	0·7889	1·0149		1·07	−35·63	− 5·43	
0·80	0·8320	1·0730		1·12	−34·62	− 4·38	
1·00	0·8678	1·1209		1·17	−34·82	− 4·38	
Size 5·04 cm							
0·05	0·4349	0·5502		0·42	3·43	23·66	
0·10	0·4907	0·6250		0·50	−1·90	20·00	
0·15	0·5276	0·6748		0·56	−6·14	17·01	
0·20	0·5559	0·7126		0·60	−7·93	15·80	
0·40	0·6313	0·8147		0·74	−17·22	9·17	
0·60	0·6816	0·8819		0·83	−21·77	5·89	
0·80	0·7203	0·9337		0·89	−29·63	4·68	
1·00	0·7518	0·9739		0·93	−23·70	4·51	

6. Effective interfacial area for physical absorption

The values of effective interfacial area for physical absorption as given by Shulman *et al*[2] (based on Fellinger's data of NH_3 absorption in water) and the calculated values from vertical surface model [eqn. (22)] are given in Table VI for Raschig rings and

Table VI

Effective interfacial area for physical absorption (cm^2/cm^3)

Superficial liquid flow rate, L cm/sec	Size 1·27 cm		Size 2·54 cm		Size 3·81 cm		Size 5·08 cm	
	From eqn. (22)	Shulman *et al*	From eqn. (22)	Shulman *et al*	From eqn. (22)	Shulman *et al*	From eqn. (22)	Shulman *et al*
Raschig rings								
0·2	0·809	0·320	0·544	0·490	0·477	0·420	0·396	0·520
0·4	0·944	0·365	0·636	0·610	0·556	0·580	0·462	0·610
0·6	1·033	0·385	0·695	0·680	0·609	0·650	0·506	0·660
0·8	1·068	0·395	0·741	0·740	0·649	0·690	0·539	0·690
1·0	1·157	0·400	0·780	0·780	0·681	0·720	0·567	0·720
Berl saddles								
0·2	0·87	0·38	0·61	0·53	0·50	0·46		
0·4	1·00	0·42	0·72	0·61	0·58	0·57		
0·6	1·10	0·46	0·79	0·69	0·64	0·61		
0·8	1·18	0·48	0·84	0·74	0·68	0·63		
1·0	1·25	0·48	0·87	0·75	0·71	0·64		

Berl saddles. From this table, it is observed that the values of effective interfacial area for physical absorption are less than those calculated from eqn. (22) for 1·2 cm Raschig rings and Berl saddles. This can be explained on the basis of stagnant liquid (liquid trapped in pockets surrounding the points of contact) which inhibits further mass transfer. This stagnant liquid gets saturated quickly and becomes ineffective for mass transfer.

The values of interfacial area calculated from eqn. (22) are in good agreement with the reported values[2] for 2·54 cm and 3·84 cm Raschig rings and are in reasonable agreement for 5·08 cm Raschig rings and 2·54 cm and 3·81 cm Berl saddles.

The values of interfacial area reported by Yoshida and Koyanagi[1] for absorption and vaporisation are given in Table VII for 2·54 cm Raschig rings along with the values

Table VII

Effective interfacial area for absorption and vaporisation on 2·54 cm Raschig rings (cm²/cm³)

Superficial liquid flow rate, L cm/sec	Absorption		Vaporisation	
	Vertical surface model eqn. (22)	Yoshida and Koyanagi[1]	Vertical surface model eqn. (24)	Yoshida and Koyanagi[1]
0·05	0·44	0·25	0·64	0·35
0·10	0·47	0·34	0·67	0·47
0·15	0·51	0·42	0·71	0·56
0·20	0 54	0·49	0·74	0·63
0·40	0·64	0·74	0·84	0·92

of interfacial area calculated by eqns. (22) and (24). This table indicates that the reported values[1] for interfacial area for absorption and vaporisation are in agreement with the calculated values except at the lower superficial liquid flow rates. This is the case even with the values of interfacial area reported for mass transfer with chemical reaction discussed earlier.

7. Conclusions

The values of interfacial area of the various sizes and shapes of packing from the vertical surface model and random angle model based on liquid hold-up have been found to be in good agreement with the reported values of wetted area by Onda *et al*[5] and the values of interfacial area by chemical methods[15] for Raschig rings and Berl saddles. Due to the complex nature of the packing geometry, the values are not in complete agreement for Pall rings and Intalox saddles. In addition, Davidson's model is strictly not applicable to Pall rings, Intalox saddles and Berl saddles, as flow cannot take place in all directions.

Nomenclature

a, a_t = geometric surface area per unit volume, cm²/cm³

a_w = wetted area per unit volume, cm²/cm³

d, D_P	=	nominal size of the packing element, cm
g	=	acceleration due to gravity
Gr	=	Grashof number, gd^3/ν^2
h	=	liquid hold-up, cm^3/cm^3 of solid free bed [eqns. (15) and (16)]
IA	=	interfacial area, cm^2/cm^3
L_m	=	mass liquid flow rate g/cm sec $L\rho$
L	=	superficial liquid flow rate, cm/sec
r	=	radius of the sphere of equivalent volume to the liquid hold-up, cm
Re	=	Reynolds number for random packing = $2\pi\ L_m/a\mu$
Re_1	=	Reynolds number for vertical surfaces = $4L_m/a\mu$
m	=	film thickness
SA	=	surface area of the sphere, cm^2
V	=	volume of the sphere of equivalent volume to the liquid hold-up, cm^3
μ	=	viscosity of the liquid, g/cm sec
ν	=	kinematic viscosity, cm^2/sec
ρ	=	density of the liquid, g/cm^3
ϵ	=	voidage of the packed bed

Subscripts

RA	=	for random angle
VS	=	for vertical surface

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