

Effective interfacial area and liquid and gas side mass transfer coefficients in a packed column

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Abstract—The theory of gas absorption accompanied by fast pseudo- m th order reaction was used to obtain values of effective interfacial area in a packed column, irrigated with aqueous solutions and provided with 1 in. ceramic Raschig rings, 1 in. P.V.C. Raschig rings, 1 in. ceramic Intalox saddles, 1 in. polypropylene Intalox saddles, 1 in. stainless steel Pall rings and 1 in. polypropylene Pall rings. The values of liquid side mass transfer coefficient were obtained by physical absorption of carbon dioxide in water. In addition, the values of gas side mass transfer coefficient for a range of gas and liquid flow rates were obtained.

INTRODUCTION

PACKED columns are used in industrial practice for absorption, humidification and distillation operations. Ceramic and stoneware packings have found wide applications in the process industries. It has been reported that polypropylene and high density polyethylene packings can be advantageously employed for a number of industrial operations. Thus, polypropylene Pall rings and Intalox saddles are used for absorption of carbon dioxide in aqueous (hot) potash solutions and alkanolamine solutions. There is a limited information in the literature on effective interfacial area, and liquid- and gas- side mass transfer coefficients provided by a number of plastic and metal packings. Recently, Danckwerts and Rizvi[1] have reported data on effective interfacial area for 1½ in. ceramic Raschig rings, 1½ in. polypropylene Pall rings, 1½ in. ceramic Intalox saddles and 2 in. polypropylene Intalox saddles. The present investigation was undertaken to provide data on effective interfacial area, and liquid- and gas- side mass transfer coefficients for a number of plastic and steel packings of 1 in. nominal size.

The theory of absorption accompanied by fast pseudo- m th order reaction was used to obtain the values of effective interfacial area. The values of liquid side mass transfer coefficient were evaluated by absorbing pure carbon

dioxide in tap water. The theory of absorption accompanied by very fast irreversible reaction was used to obtain the values of gas side mass transfer coefficient.

THEORETICAL TREATMENT AND METHODS OF ANALYSIS

The theoretical aspects and systems that could be conveniently used have been discussed in detail by Jhaveri and Sharma[2], Sharma and Mashelkar[3] and Sharma and Danckwerts[4]. It was decided to absorb oxygen from air in dithionite solutions to obtain values of effective interfacial area. In addition, some experiments were made with absorption of lean carbon dioxide in aqueous caustic soda and diethanolamine solutions to obtain values of effective interfacial area. For obtaining gas side mass transfer coefficient lean sulfur dioxide or chlorine was absorbed in aqueous caustic soda solutions. Vidwans and Sharma[5] and Sharma and Mashelkar[3] have discussed the methods of analysis pertinent to the various systems.

EXPERIMENTAL

A schematic diagram of the experimental set-up is shown in Fig. 1. The work was carried out in a 20 cm i.d. perspex column provided with a cross-armed multipoint liquid distributor and a gas injection type of gas distributor. Most of the

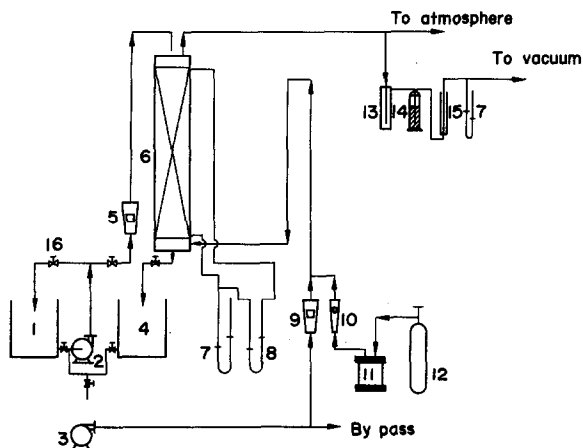


Fig. 1. Experimental set-up. 1. Storage tank (Feed), 2. Pump, 3. Blower, 4. Storage tank (outlet), 5. Liquid Rotameter, 6. Packed column, 7. Barometer, 8. Manometer, 9. Air rotameter (Carrier), 10. Solute gas rotameter, 11. Surge vessel, 12. Solute gas cylinder, 13. Trap, 14. Scrubber, 15. Soap-film meter, 16. Control valves.

experiments for effective interfacial area and liquid side mass transfer coefficient were carried out at a packed height of about 87 cm and that for gas side mass transfer coefficient at a packed height of about 61 cm.

The solute and the carrier gases were metered precisely by accurately calibrated rotameters. The absorbent solution was sent to the column by a pump through a rotameter. The actual liquid flow rate was measured for each experiment by collecting the outgoing liquid in a measuring cylinder. The liquid rotameter was used to ensure that the liquid flow rate remained essentially constant during an experimental run.

Air was supplied by an air blower and solute gases from cylinders. To ensure proper mixing of the solute with the carrier gas, a mixing length of over 200 times the diameter of the pipe carrying the gas mixture was provided. The absorbent solution was allowed to flow through the column for about 15 minutes before starting the actual experiment.

In the case of experiments for gas side mass transfer coefficient, a bleed from the outgoing gas was scrubbed in a suitable absorbent which completely removed the solute and the solution was

subsequently analysed. It is necessary to base the calculation of gas side mass transfer coefficient on the analysis of outgoing gas stream rather than on the basis of the analysis of liquid streams and material balance because an insignificant error in the liquid analysis can affect the coefficient significantly [5].

Some experiments for liquid side and gas side mass transfer coefficients were carried out at two different depths of packing. The values so obtained agreed closely indicating that there were no appreciable end effects.

Table 1 lists the salient characteristics of the packings employed.

RESULTS AND DISCUSSION

Effective interfacial area

Figure 2 shows the variation of effective interfacial area with superficial liquid velocity for 1 in. stainless steel Pall rings, 1 in. ceramic Intalox saddles and 1 in. ceramic Raschig rings.

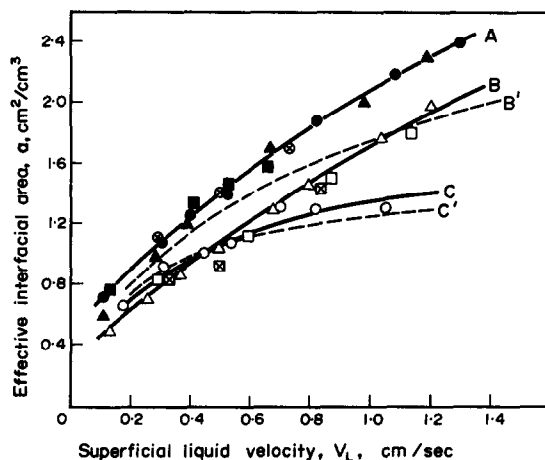


Fig. 2. Effect of liquid flow rate on effective interfacial area. Curve A: 1 in. Stainless Steel Pall rings, ● Dithionite-air system (1st order region) $V_G = 21.1$ cm/sec, ▲ Dithionite-air system (2nd order region), $V_G = 21.1$ cm/sec, ■ NaOH- CO_2 system, $V_G = 30$ cm/sec, ⊗ DEA- CO_2 system, $V_G = 30$ cm/sec. B: 1 in. Ceramic Intalox saddles, □ Dithionite-air system (1st order region), $V_G = 21.1$ cm/sec, △ NaOH- CO_2 system, $V_G = 21.6$ cm/sec, ⊠ DEA- CO_2 system, $V_G = 30$ cm/sec. C: 1-in. Ceramic Raschig rings, ○ Dithionite-air system (1st order region), $V_G = 30$ cm/sec. B': 1 in. Ceramic Intalox saddles (Mannford Doble). C': 1 in. Ceramic Raschig rings (Mannford Doble).

Effective interfacial area

Table 1. Characteristics of packings

	Number/m ³		Geometrical surface area (cm ⁻¹)	Free space (%)
	(a)	(b)		
1 in. Ceramic Raschig rings	48000	50600	1.9	74
1 in. P.V.C. Raschig rings (wall thickness = $\frac{1}{16}$ in.)	48000†	51400	1.9†	74†
1 in. Ceramic Intalox saddles.	84500	75300	2.54	77
1 in. Polypropylene Intalox saddles	56000	53500	2.06	92
1 in. Stainless steel Pall rings.	50000	49000	2.06	94
1 in. Polypropylene Pall rings.	50500	51000	2.06	90

†Taken as that of Ceramic rings.

(a) Stated by Manufacturers.

(b) Observed.

Figure 3 is a plot of effective interfacial area against superficial liquid velocity for 1 in. plastic packings.

Mannford Doble (as cited in Ref. [6]) has also obtained values of effective interfacial area as a function of superficial liquid velocity for 1 in. ceramic Raschig rings and 1 in. ceramic Intalox saddles by the chemical method and these are also shown in Fig. 2. The agreement for Raschig rings is quite close. However, in the case of 1 in. ceramic Intalox saddles our values of interfacial area are about 25 per cent lower than those of Mannford Doble, below superficial liquid velocity of about 1.0 cm/sec. In the case of Intalox saddles, the packing density in our work was 75300 pieces/m³ which may be compared with the corresponding value of 84000 pieces/m³ reported by Mannford Doble. The lower values of the effective interfacial area obtained in our work could, therefore, be at least partly attributed to the lower packing density.

It is seen from Fig. 3 that all the plastic packings, though having nearly the same geometrical surface area and packing density give different values of effective interfacial area at any specified superficial liquid velocity. This indicates that apart from other factors, the shape of the packing is also important. Polypropylene

Pall rings show lower values of interfacial area than the polypropylene Intalox saddles and P.V.C. Raschig rings. This may be attributed to the shape of the packing. The construction of the Pall ring is such that it does not offer continuous surface for the liquid stream to be spread on its surface. Polypropylene Intalox saddles and P.V.C. Raschig rings, which offer continuous surfaces for spreading of liquid, show higher values of effective interfacial area than polypropylene Pall rings.

The importance of wettability and shape could be seen when the values of effective interfacial area are compared for stainless steel Pall rings, ceramic Raschig rings and ceramic Intalox saddles. Though stainless steel Pall ring is less wettable than ceramic packings, it offers the highest values of interfacial area.

On a comparative basis, the values of effective interfacial area offered by stainless steel Pall rings are about 70 per cent higher than those offered by plastic Pall rings. Amongst the plastic packings the highest values of effective interfacial area are offered by 1 in. polypropylene Intalox saddles. Thus, for instance, the values of effective interfacial area offered by polypropylene Intalox saddles are about 40 per cent higher than those offered by polypropylene Pall rings.

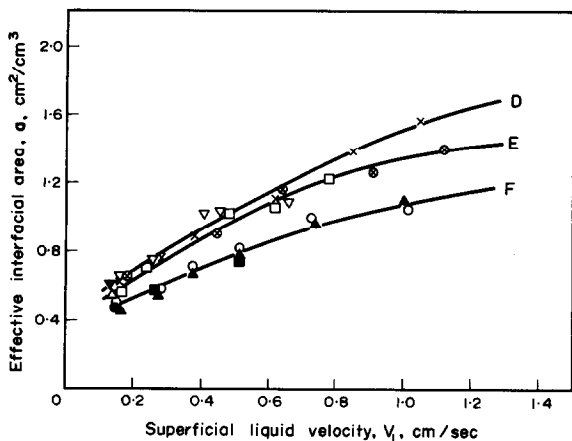


Fig. 3. Effect of liquid flow rate on effective interfacial area. Curve D: 1 in. Polypropylene Intalox saddles. ∇ Dithionite-air system (1st order region), $V_G = 21.1$ cm/sec,

- $\times V_G = 21.6$ cm/sec } NaOH-CO₂ system.
- $\Delta V_G = 15.0$ cm/sec } NaOH-CO₂ system.
- E: 1 in. P.V.C. Raschig rings. \otimes Dithionite-air system (1st order region), $V_G = 21.1$ cm/sec,
- $\square V_G = 21.6$ cm/sec } NaOH-CO₂ system.
- $\nabla V_G = 15.0$ cm/sec } NaOH-CO₂ system.
- F: 1 in. Polypropylene Pall rings. \otimes Dithionite-air system (1st order region), $V_G = 21.1$ cm/sec,
- $\blacksquare V_G = 26.2$ cm/sec } NaOH-CO₂ system.
- $\blacktriangle V_G = 21.6$ cm/sec } NaOH-CO₂ system.
- $\bullet V_G = 15.0$ cm/sec } NaOH-CO₂ system.

It is, however, surprising to find that the values of effective interfacial area offered by 1 in. ceramic Raschig rings and 1 in. P.V.C. Raschig rings are comparable.

Liquid side mass transfer coefficient

It would have been advantageous in some respects to adopt the chemical method for obtaining liquid side mass transfer coefficient by absorption of carbon dioxide in carbonate buffer solutions[4]. However, in the case of packed columns the necessary conditions for the case of the above method are not satisfied. Consider a typical case where:

- pseudo first order rate constant for the reaction of carbon dioxide, $k_1 = 3.0$ sec⁻¹,
- the diffusivity of carbon dioxide in the solution, $D_L = 1.8 \times 10^{-5}$ cm²/sec,
- the true liquid side mass transfer coefficient,

$k_L = 8 \times 10^{-3}$ cm/sec; the fractional liquid hold up, $l = 0.10$. In this case the condition,

$$lk_1 \gg k_L a$$

is satisfied ensuring that there is no dissolved unreacted carbon dioxide in the bulk. However, in the condition,

$$\frac{\sqrt{D_L k_1}}{k_L} \ll 1$$

the left hand side term becomes comparable to unity showing that there is some reaction in the film.

Thus, in view of the above it was decided to use the physical absorption method for obtaining values of liquid side mass transfer coefficient.

Figure 4 shows the effect of superficial liquid velocity on liquid side mass transfer coefficient for various 1 in. packings employed. The values of liquid side mass transfer coefficient obtained for all the plastic packings are practically the same at any specified value of the superficial liquid velocity.

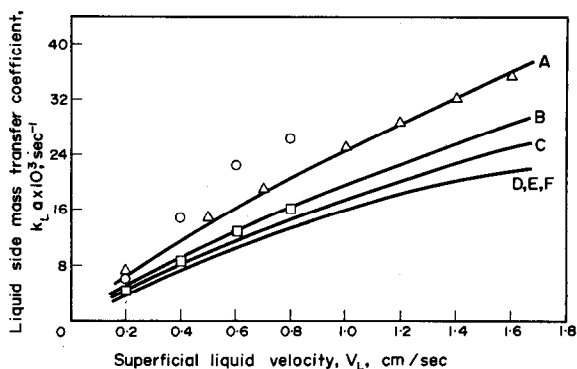


Fig. 4. Effect of liquid flow rate on liquid side mass transfer coefficient.

- Curve A: 1 in. Stainless Steel Pall rings } Absorption of pure CO₂ in tap water.
- B: 1 in. Ceramic Intalox saddles }
- C: 1 in. Ceramic Raschig rings }
- D: 1 in. Polypropylene Intalox saddles }
- E: 1 in. P.V.C. Raschig rings }
- F: 1 in. Polypropylene Pall rings }
- Δ By Norman's Generalised Correlation for Raschig Rings and Berl saddles,
- \square 1 in. Ceramic Raschig rings } Values by Mannford Doble.
- \circ 1 in. Ceramic Intalox saddles }

The liquid side mass transfer coefficient, $k_L a$, depends on both, the true liquid side mass transfer coefficient, k_L , and the effective interfacial area, a . The fact that interfacial area is different for all the packings, indicates that the flow characteristics of the liquid over packings are different. It is likely that the variation in a partially offsets the variation in k_L in such a way that the $k_L a$ values are practically the same for all the plastic packings. Thus, Norman[7] has shown that even for different size packings ($\frac{3}{8}$ -2 in. Raschig rings and $\frac{1}{2}$ -1 $\frac{1}{2}$ in. Berl saddles) where the values of effective interfacial area are markedly different, $k_L a$ can be predicted within ± 20 per cent by the following generalized correlation:

$$\frac{k_L a}{D} = 120 \left(\frac{L}{\mu_L} \right)^{0.75} \left(\frac{\mu_L}{\rho_L D} \right)^{0.5} \quad (1)$$

where,

$k_L a$ = liquid side mass transfer coefficient, hr^{-1}

L = liquid flow rate, lb/hr ft^2

μ_L = viscosity of the liquid, ft/lb/hr units

ρ_L = density of the liquid, ft/lb/hr units

D = diffusivity of the dissolved carbon dioxide, ft/lb/hr units .

The values obtained from Norman's generalized correlation (for Raschig rings) are also plotted in Fig. 4. The calculated values are about 45 per cent higher than those obtained experimentally for ceramic Raschig rings. Our values agree with those obtained by Yoshida and Miura [8] from absorption of carbon dioxide in water. The packing density reported by Yoshida and Miura [8] is almost the same as that observed in this work. Mannford Doble (as cited in Ref. 6) has also obtained values of liquid side coefficient as a function of superficial liquid velocity for 1 in. ceramic Raschig rings and Intalox saddles. The agreement for Raschig rings is within 10 per cent. However, our values of $k_L a$ for 1 in. ceramic Intalox saddles are about 35 per cent lower than those of Mannford Doble, as can be seen in Fig. 4. The values of $k_L a$ for 1 in. ceramic Intalox saddles as reported by Mannford Doble seem to

vary as $V_L^{0.95}$. The exponent of 0.95 appears to be on the higher side.

The data on liquid side mass transfer coefficient were correlated by the following equation:

$$k_L a = \alpha (V_L)^\gamma \quad (2)$$

where, V_L = superficial liquid velocity, cm/sec . Table 2 lists the constants and exponents of Eq. (2) for various packings.

Coughlin[9] has reported data on overall liquid side mass transfer coefficient for $\frac{3}{8}$ in.

Table 2. Exponents and constants of Eq. (2)

	α	γ
1 in. Ceramic Raschig rings	17.2×10^{-3}	0.806
1 in. Ceramic Intalox saddles	20.0×10^{-3}	0.806
1 in. Stainless Steel Pall rings	25.2×10^{-3}	0.806
1 in. Plastic Packings	16.0×10^{-3}	0.784

Raschig rings made of ceramic, polyethylene and Saran (a copolymer of vinyl and vinylidene chloride). The values of overall liquid side mass transfer coefficient were the same for both Saran and polyethylene rings and were about 25 per cent lower than the ceramic rings. Coughlin[9] has reported that the overall liquid side mass transfer coefficient, $K_L a$ varies as $L^{0.452}$. This exponent appears to be on the lower side. Thus, Sherwood and Holloway[10] have reported an exponent of 0.54 of liquid flow rate, L for $\frac{3}{8}$ in. Raschig rings. Further, for instance, for $\frac{3}{8}$ in. ceramic Raschig rings Vidwans and Sharma[5] have found that the effective interfacial area, a varies as $V_L^{0.3}$. It would be expected that liquid film coefficient, k_L would vary with about 0.2-0.3 power of liquid flow rate. In the generalized correlation of Norman[7] which includes $\frac{3}{8}$ in. Raschig rings also, $k_L a$ varies as $L^{0.75}$.

An improvement of over 60 per cent was obtained for the stainless steel Pall rings over plastic packings. The liquid side mass transfer coefficient for plastic packings are the lowest of those obtained for the packings studied. The $k_L a$ values for ceramic Raschig rings are about 15 per cent higher than those for plastic packings.

Gas side mass transfer coefficient

The values of gas side mass transfer coefficient were obtained for various 1 in. packings. The values of gas side mass transfer coefficient for one of the packings, 1 in. polypropylene Intalox saddles, are plotted against superficial liquid velocity with superficial gas velocity as parameter in Fig. 5.

The data on gas side mass transfer coefficient were correlated by the following equation:

$$k_G a = \beta (V_G)^m (V_L)^n \quad (3)$$

where, V_G : superficial gas velocity, cm/sec

V_L : superficial liquid velocity, cm/sec.

Table 3 lists the constants and the exponents of Eq. (3) for various packings employed.

Whitney and Vivian[11] have reported some data on absorption of lean SO₂ in water in a packed column provided with 1 in. ceramic

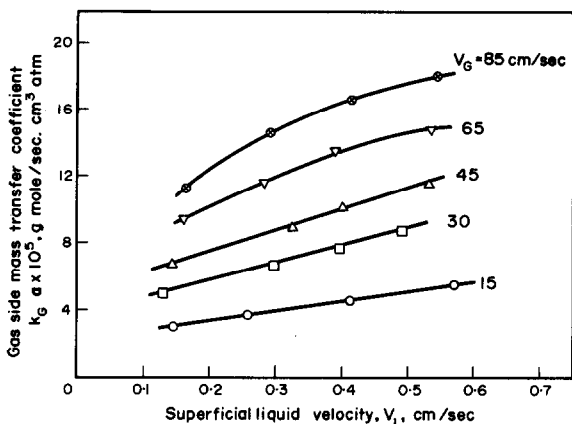


Fig. 5. Effect of superficial liquid and gas velocity on gas side mass transfer coefficient for 1 in. polypropylene intalox saddles with NaOH-Cl₂/air system.

Table 3. Exponents and constants of Eq. (3)

	β	m	n
1 in. Ceramic Raschig rings	1.28×10^{-5}	0.64	0.48
1 in. P.V.C. Raschig rings	0.81×10^{-5}	0.735	0.41
1 in. Ceramic Intalox saddles	1.3×10^{-5}	0.70	0.48
1 in. Polypropylene Intalox saddles	0.92×10^{-5}	0.75	0.45
1 in. Stainless Steel Pall rings	2.29×10^{-5}	0.58	0.38
1 in. Polypropylene Pall rings	1.18×10^{-5}	0.68	0.47

Raschig rings and found that $k_G a$ varies as $L^{0.25}$. Dwyer and Dodge[12] have reported that $k_G a$ varies as $L^{0.2}$. The values of exponent of liquid flow rate, L , are rather unrealistic as can be seen from our data on variation of effective interfacial area, a with the superficial liquid velocity, V_L .

Figure 6 shows that the true gas side mass transfer coefficient is independent of the liquid flow rate at any specified superficial gas velocity in the range of gas velocity studied. It appears, therefore, that the effect of liquid rate on the gas side mass transfer coefficient, $k_G a$, at a given gas rate, can be accounted for entirely in terms of the variation of effective interfacial area with the liquid flow rate.

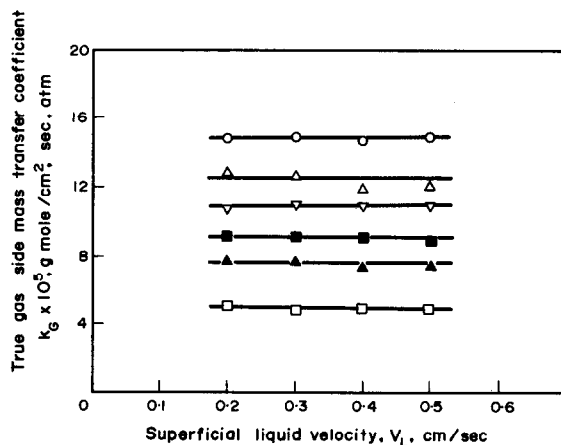


Fig. 6. Effect of superficial liquid velocity on gas film coefficient. \circ 1 in. Stainless Steel Pall rings ($V_G = 65$ cm/sec), Δ 1 in. Ceramic Intalox saddles ($V_G = 45$ cm/sec), ∇ 1 in. Polypropylene Intalox saddles ($V_G = 45$ cm/sec), \blacksquare 1 in. Polypropylene Pall rings ($V_G = 25$ cm/sec), \blacktriangle 1 in. P.V.C. Raschig rings ($V_G = 30$ cm/sec), \square 1 in. Ceramic Raschig rings ($V_G = 15.4$ cm/sec).

CONCLUSIONS

1. The values of effective interfacial area offered by various 1 in. packings differ substantially. Polypropylene Intalox saddles are better than the polypropylene Pall rings. Highest values are offered by stainless steel Pall rings.

2. The values of liquid side mass transfer coefficient, at any specified superficial liquid velocity, are practically the same for all the plastic packings used irrespective of their

Effective interfacial area

shape. Ceramic packings are better than the plastic packings. The best performance was shown by stainless steel Pall rings.

3. The values of true gas-side mass transfer coefficient are independent of the superficial liquid flow rate, at any specified superficial gas velocity.

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NOTATION

a effective interfacial area per unit volume of packing, cm^2/cm^3
 D_L diffusivity of solute in the liquid, cm^2/sec

k_1 pseudo first order reaction rate constant, sec^{-1}
 k_G true gas side mass transfer coefficient, $\text{g mole}/\text{cm}^2 \text{ sec atm}$.
 k_L true liquid side mass transfer coefficient, cm/sec
 l fractional liquid hold up
 m, n exponents in Eq. (3)
 V_G superficial gas velocity, cm/sec
 V_L superficial liquid velocity, cm/sec

Greek symbols

α constant in Eq. (2)
 β constant in Eq. (3)
 γ exponent in Eq. (2)

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