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기-액 흡수계에서 Spiral Wires-Radial Plates 충전물의 진동효과

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The Vibration Effects of Spiral Wires-Radial Plates Packing in Gas-Liquid Absorption

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요 약

본 연구는 기-액 흡수 물질전달계에서 충전-진동에 의하여 물질전달 속도를 증가시키는 연구로서 충전탑에 새로 고안한 Spiral Wires-Radial Plates를 충전시키고, 진동을 주어 물질전달에 미치는 제반 영향을 측정 분석하였다.

가스유속의 변화에 따른 가스 hold-up과 Danckwerts Plots법에 의한 기-액계 면적 및 액측 물질전달 계수를 측정하였으며 물질전달 인자간의 상호관계를 규명하고 정량적 관계식을 제시하였다.

ABSTRACT

This study was concerning to improve the mass transfer rate by packing-vibration and to investigate the relationship among the mass transfer factors in the gas-liquid contact absor-

ption system.

The gas-liquid contact mass transfer system was operated by the vibration of the newly designed spiral wires-radial plates packing in the column. The gas hold-up, gas-liquid interfacial areas and liquidside mass transfer coefficients were measured and analyzed, and a quantitative mass transfer equation on this absorption system was presented.

1. Introduction

Efforts to improve mass transfer rates in countercurrent columns contacting gas-liquid or liquid-liquid systems have been extensive. Improved packing has been developed by Voyer and Miller,[20] Chen[3,4] Kim,[12,13] Mashelker,[15] and Sahay[18] among others. Improvement through the vibration of the packing or the fluid has been prepared by Buchanan,[2] Bretsznajder and Pasiuk[1], and by Jameson and Davidson.[9]

The aim of this study is to develop a simple and effective mass transfer column which can be successfully used both for liquid-liquid and for gas-liquid contacting. The design was chosen with combination of the spiral wires used earlier by Kim[12,13] with the radial plates reported by Karr[10,11] in an oscillating arrangement.

Using such a system mass transfer factors including gas holdup, gas-liquid interfacial area, and mass transfer coefficient were measured and compared with results of conventional systems. Initially the air-water system was used, but later experiments were done by contacting an air-CO_2 phase with potash solution. As yet no work has been done with liquid-liquid system.

2. Theoretical Approach

Vibration effects in a gas-liquid contacting system operate through the perturbation of the gas-liquid interface. Energy applied to the system may produce wave action in the bubble coalescence. In the system described here vibration is of modest intensity, and the perturbation of the interface by pressure waves is considered to be the dominant effect of plate vibration.

The intensity of the reciprocating motion will affect the intensity of pressure wave transmitted to the interface which will, in consequence, affect the mass transfer rate. In the development that follows it is assumed that the column, in which the liquid phase is continuous, is in static state but moving vertically in simple harmonic motion as the plates and wires are similarly moved. It is also assumed that gas bubble radii are not affected by the reciprocating motion.

When the liquid column with contained gas bubbles is vibrated in the vertical plane by simple harmonic motion of amplitude A and circular frequency ω, the pressure acting on the bubble surface will result from system pressure, hydrostatic head, and moment changes in the liquid phase:

$$P_s = P_0 + \rho gh - \rho hA\omega^2 \sin\omega t \qquad (1)$$

The term $\rho hA\omega^2 \sin\omega t$ is the pressure effect caused by momentum changes resulting from the harmonic motion.

This is called the fluctuation pressure, P_s'.

Taking the root mean square value of the fluctuation pressure,

$$\tilde{P}_s' = [(\bar{P}_s')^2]^{\frac{1}{2}} = \left[\int_0^{2\pi/w} (P_s')^2 dt \Big/ \int_0^{2\pi/w} dt\right]^{\frac{1}{2}}$$

$$= \frac{h}{\sqrt{2}} \rho A \omega^2 \qquad (2)$$

Therefore, the mean fluctuation pressure affecting the gas bubble interface is

$$\tilde{P}_I' = \tilde{P}_s' B = \frac{h}{\sqrt{2}} \rho B A \omega^2 \qquad (3)$$

Where B is a correction factor for viscous damping on the surface.[19] The term $\tilde{P}_I$ can now be included in expressions relating mass transfer effects to the intensity of harmonic oscillation.

The fluctuation component of the velocity of the gas bubble interface can be expressed as a linear function between the limits

$$\tilde{V}_x' = (V_0 + \tilde{V}'_v)\psi(x) \text{ at } y = 0 \qquad (4)$$

$$\tilde{V}_x' = V_0 \psi(x) \qquad \text{at } y = \lambda / c \qquad (5)$$

Where $\tilde{V}_x'$ is the fluctuation velocity component in the x-direction parallel to the interface.

$\tilde{V}_v'$ is the fluctuation velocity component in the plane of the interface due to fluctuations in interfacial tension.

If we assume that $\tilde{V}_x'$ varies linearly as proposed above, and apply the continuity equation[14]

$$\tilde{V}_y' = -\left[\int\left(\frac{\partial \tilde{V}_x'}{\partial x}\right)_y dy\right]_x = -[(V_0 + \tilde{V}_v')y - \frac{cy^2}{2\lambda}\tilde{V}_v']\psi(x) \qquad (6)$$

$$If\ \psi(x) = -\frac{1}{\lambda}$$

$$\tilde{V}_y' = \frac{y}{\lambda}\left[(V_0 + \tilde{V}_v) - \frac{cy}{\lambda}\tilde{V}_v'\right] \qquad (7)$$

In the laminar sublayer around the gas bubble[8,14,16]

$$y = \frac{D}{0.4\tilde{V}_y'} \qquad (8)$$

$$\lambda = \frac{\sigma}{\rho V_0^2} \qquad (9)$$

$$\tilde{P}_I' = \rho \tilde{V}_v'^2 \qquad (10)$$

and therefore, rearranging Equation (10) and replacing $\tilde{P}_I'$ from Eq. (3) gives

$$\tilde{V}_v' = \sqrt[4]{\frac{h^2}{2}}(BA\omega^2)^{1/2} \qquad (11)$$

The thickness of the laminar sulayer can now be fixed by putting $D = D_E$ when $y = \delta$ and using equations (7), (8) and (9)

$$\delta = \left(\frac{D_E \sigma}{0.4 \rho V_0^3}\right)^{1/2}\left[1 + \frac{\tilde{V}_v'}{V_0}\right]^{1/2} \qquad (12)$$

Using Equation (12) and the Levich Model[7,14] the mass transfer coefficient for the absorption column with its packing in harmonic oscillation can be expressed as

$$K_{L,V} = \left(\frac{0.1 D_E \rho V_0^3}{\sigma}\right)^{1/2}\left[1 + \frac{\tilde{V}_v'}{V_0}\right]^{1/2} \qquad (13)$$

where $K_{L,V}$ is the overall mass transfer coefficient in terms of liquid phase driving force units with the system in hormonic oscillation. In the case of a column, packed but without vibration, $K_{L,P}$ is

$$K_{L,P} = \left(\frac{0.1\ D_E \rho V_0^3}{\sigma}\right)^{1/2} \qquad (14)$$

So the ratio of mass transfer coefficients, the coefficients when the column is vibrated as related to that when the column is not vibrated, is

$$R = \frac{K_{L,V}}{K_{L,P}} = \left[1 + \left(\frac{\frac{h}{\sqrt{2}} B A \omega^2}{V_0^2}\right)^{1/2}\right]^{1/2} \qquad (15)$$

$$\text{or} \quad R^2 = \left[1 + \left(\frac{\frac{h}{\sqrt{2}} B}{V_0^2}\right)^{1/2}(A\omega^2)^{1/2}\right] \qquad (16)$$

3. Experimental Method

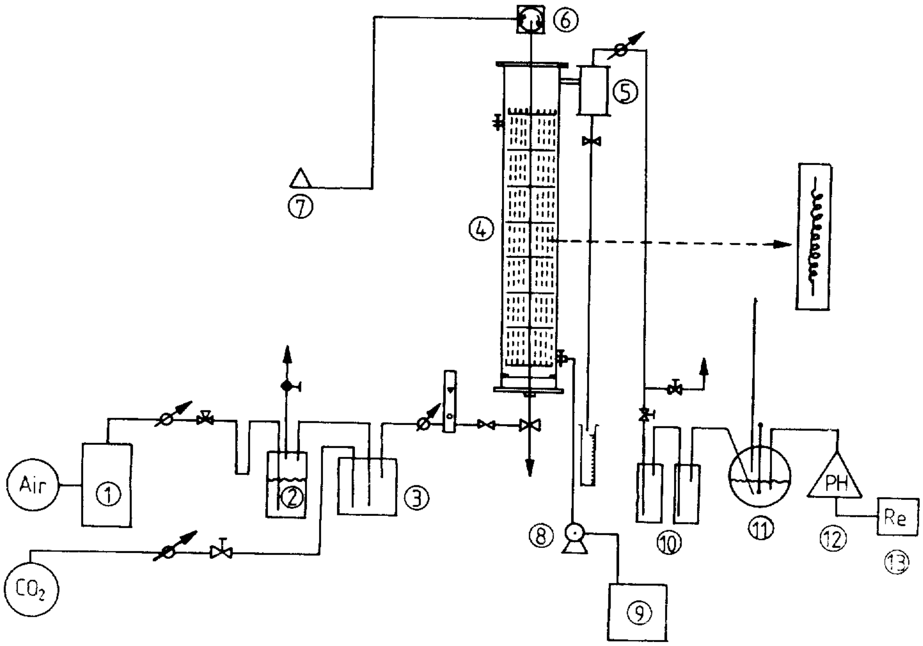
In order to determine the packing design and vibration effects in gas-liquid contacting, gas holdup and mass transfer effectiveness as determined by gas-liquid interfacial area, the liquid phase mass transfer coefficient and volumetric mass transfer coefficient were measured. Initially these data were obtained for an empty column, then in the column with packing but without vibration, and finally in the column with the packing oscillatory.

The experimental apparatus is shown in *Figs. 1* and *2*. The tower consisted of a 7.6 cm ID x 91 cm high acrylic cylinder. Eight spiral wires ran vertically through the column which was interrupted by eight four-armed plates at 10 cm plate-to-plate distances. The spiral wires were 0.4 mm thick stainless steel coiled in a 6 mm diameter circle with a 12 mm pitch. These wires were strung between perforated stainless steel end plates that were 0.7 mm thick having 9 holes of 1.2 mm diameter. Vibration was obtained by attaching a central rod to a motor-driven cam with a 4.8 cm maximun off-set. Both the frequency of rotation and the cam length could be varied, though here only frequency was changed.

Operating condition for the column are reported in *Table 1*. Initially the column was run using air and distilled water to determine gas-holdup variations. Operation occurred with air flow but without liquid circulation. When the air flow was abruptly stopped the gas holdup could be measured as the fraction of the column that was empty. The gas holdup and bubble rising velocity were then calculated from the relationships.[12]

$$\phi = \frac{Q}{h_0 S}$$

$$\bar{U}_r = \frac{\bar{U}_g}{\phi}$$



① Air holding tank
② Air-water saturator
③ Mixing bottle
④ Spiral wire-rradial plate packed column
⑤ Gas-liquid separator
⑥ Vibrator
⑦ Vibration controller
⑧ Solution feeding pump
⑨ Solution tank
⑩ $FeSO_4$ solution bottles
⑪ Distilled water flask
⑫ PH meter
⑬ Recorder

Fig. 1. Flowchart for Experimental Apparatus

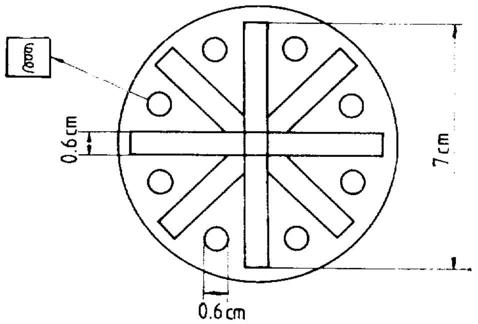


Fig. 2. Top view of Spiral wires-Radial plate packing in the Column

Table 1. Experimental Operating Conditions

• Superficial gas velocity	: 5.2−24.2cm/sec
• Total pressure	: 1.03±0.01 atm
• Potash solution	: K_2CO_3(0.6gmole/l), $KHCO_3$(0.25〃) KCl(1.92〃), NaOCl(0−0.27) σ : 80dyne/cm, $D \cong 1.35 \times 10^{-5} cm^2/sec$
• Liquid density	: 1.15−1.18 gr/cm³
• Liquid viscosity	: 1.16−1.30 C.P.
• PH	: 10.4
• Froth height	: 79cm±0.6.cm
• Temperature (column)	: 23±2°C
• Vibration stroke (Amplitude)	: 3.3cm
• Frequency range	: 1st(200rpm) 2nd(260rpm) 3rd(325rpm) 4th(380rpm)

The gas-liquid interfacial area and mass transfer coefficients were measured using the air + CO_2 and potash solution system. CO_2 and liquid phase concentrations, and physicochemical properties were measured by methods reported earlier.[13]

The variations in mass transfer coefficients and gas liquid interfacial area determinable using the Danckwerts plot graphical method[5,6] based on the rate equation of the form

$$\left(\frac{Ra}{A^* \sqrt{D}}\right)^2 = a^2 K_1 + \left(\frac{K_L a}{\sqrt{D}}\right)^2$$

4. Results and Discussion

Figures 3 and *4* show the results obtained on gas holdup and gas bubble rising rate using the air-water system. The gas holdup, shown in *Fig. 3*, increased with increasing gas flow rate whether or not packing was present in the column and regardless of the state of vibration of the packing. The holdup was greatest for vibrated packing, increasing with increasing vibration frequency. The holdup was lowest in the empty coumn obviously column internals impede bubble rise and increase gas holdup. Within the conditions expressed here vibration of the packing intensifies this retardation.

The bubble rising rate shown in *Fig. 4* is much less sensitive to gas flow rate than is the holdup. However the retardation effect of the packing, and especially of vibrated packing is still evident,

The mass transfer performance of the absorption column is shown in the Danckwerts plots given as *Figures 5-11*. *Figs. 5* and *6* are for the empty column and column with spiral wires-radial plates but without vibration, respectively. *Figs. 7-11* are for the packed column with vibration present. Each of these plots is for a fixed gas flow rate but gives lines for each of the four levels of vibration frequency used. The interfacial area, mass transfer coefficient, and volumetric mass transfer coefficient, $K_L a$, obtained by analysis of these data are shown in *Figs. 12-14*.

As shown in *Fig. 12*, the gas-liquid interfacial area increases with an increase in superficial gas velocity for all of the column arrangements considered. This increase is reduced when the column packing is vibrated. For the packed column the interfacial area is about 50% greater than for the empty column regardless of superficial gas velocity. With vibrated packing the increase is even greater, though the gas velocity effects is reduced. The average increase due to vibration is about 20%. As mentioned above it is presumed that vibration inhibits gas bubble rising, and contributes to the break-up of the natural gas bubble coalesence.[17]

Fig. 13 shows the effect of superfical gas velocity on mass transfer coefficieient, K_L. Obviously there is no significant interrelationship in these variables, but the effects of the presence of packing and vibration are large. The mass transfer coefficient is increased over 3 fold by the presence of packing and another 50% by vibration of minimal frequency. The vibration effect increases as the frequency increases. These effects are ascribed to the interfacial turbulence caused by the packing and enhanced by the vibration.

These two effects are combined in the volumetric mass transfer coefficient which is plotted in *Fig. 14*. Also shown on this figure are results from previous workers[4,18,20] These literature values were selected because those experimental systems were almost the same as this present work.

The volumetric mass transfer coefficients obtained here, both with the stationary packing and the vibrating packing are much greater than reported by these workers.

As these results show, the spiral wire-radial plates packing with vibration gives enhanced mass transfer rate, mass transfer coefficients, interfacial area and gas holdup when compared with the stationary packing or with an empty column. It is postulated that this enhanced performance results both from packing geometry and from the transfer of energy from the packing to the fluid system, not only were gas bubble retained for a longer time in the column, but they were dispersed by the packing movement. In all cases the effect of vibration is large. Even at the highest gas velocity, where the vibration effect is least the increase is in the order of 150% to 50%.

Fig. 15 compares the experimental mass transfer results obtained using the vibrated packing with the prediction of Equation (16). The line representing Equation (16) on that figure was given a slope appropriate to the data obtained.

From this B = 0.021 so that the correlating equation for this system is

$$R^2 = \left[1 + \left(\frac{\frac{0.021h}{\sqrt{2}}}{V_0^2}\right)^{1/2} (A\omega^2)^{1/2}\right] \qquad (17)$$

This correlation does'nt completely compensate for variations in gas flow rate, but it does correlate the results so as to give a maximum deviation in R^2 of 22%, and a root-mean-square deviation in R^2 of $\pm 9.8\%$.

5. Conclusions

The spiral wire-radial plate packing used here has been shown to improve markedly in its mass transfer performance through the effects of packing vibration. An increase in vibrational frequency increased gas holdup and mass transfer coefficient. The presence of unvibrated packing increased the interfacial area and mass transfer coefficient by about 40% and 220% respectively in comparison

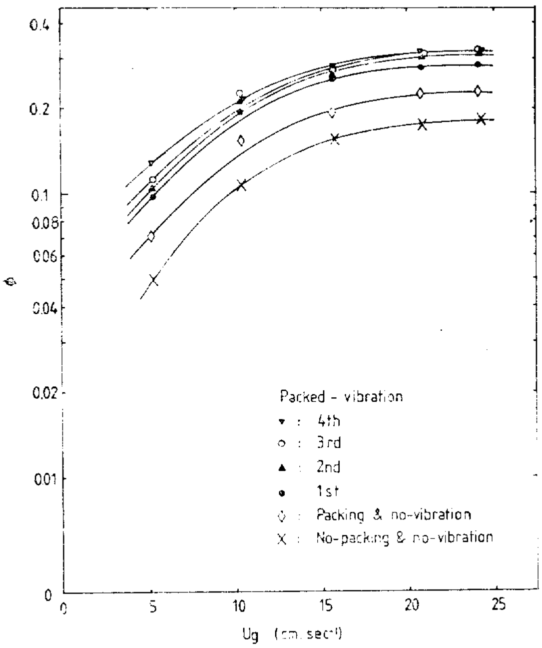


Fig. 3. Relationship between gas hold up (ϕ) and superficial gas veloicty with various variations

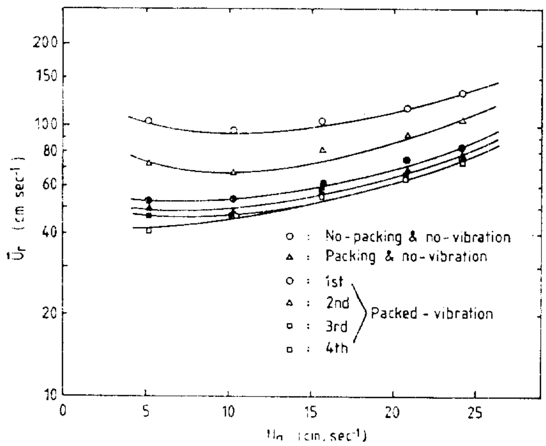


Fig. 4. Relationship between average rising velocity of bubble($\bar{U}_r$) and superficial gas velocity with various variations

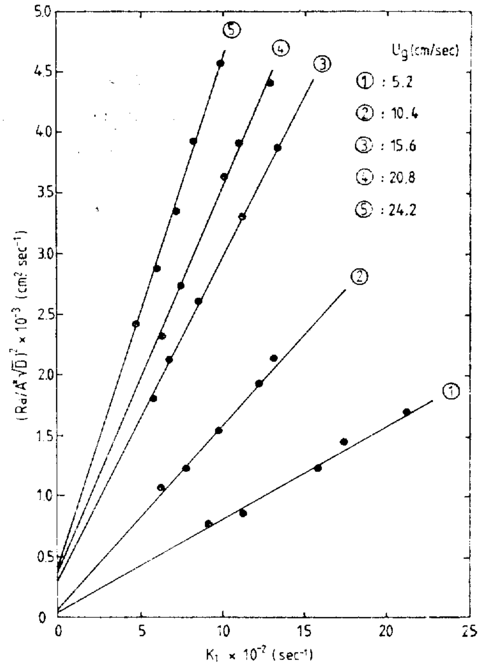


Fig. 5. Danckwerts plots in the no-packing system

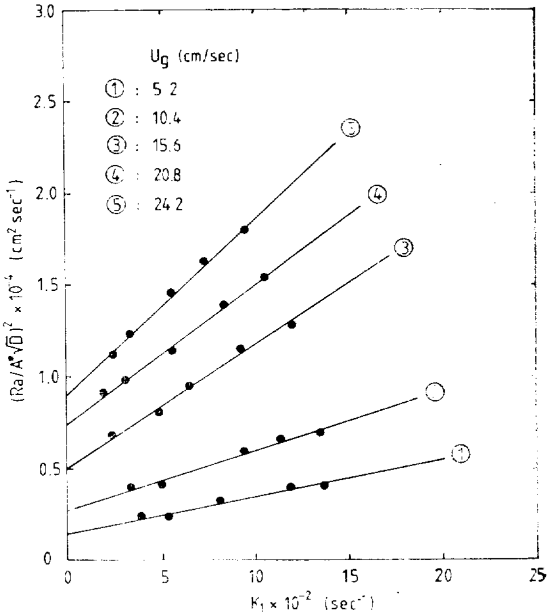


Fig. 6. Danckwerts plots in the packing system

to the performance of an empty column. With the vibrated packing these increases were about 70% and 380% respectively.

For the gas absorption system studied here volumetric mass transfer coefficients were superior to other vibrated packings reported in the literature.[4,8,20]

Finally, the relationship developed here through a consideration of the pressure wave effect of packing vibration did account for the measured transfer coefficients within a root mean square deviation of 10%.

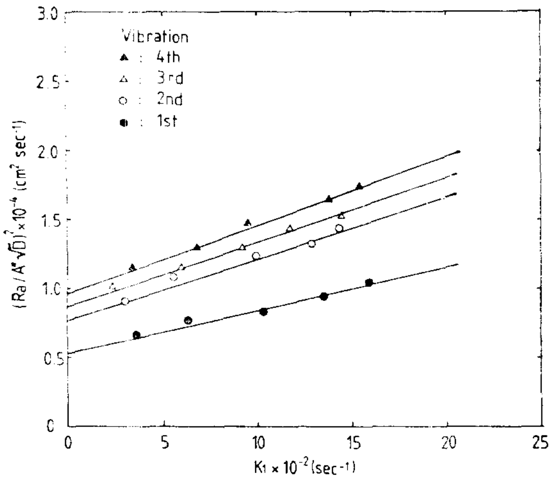


Fig. 7. Danckwerts plots in the packed-vibration system at U_g=5.2

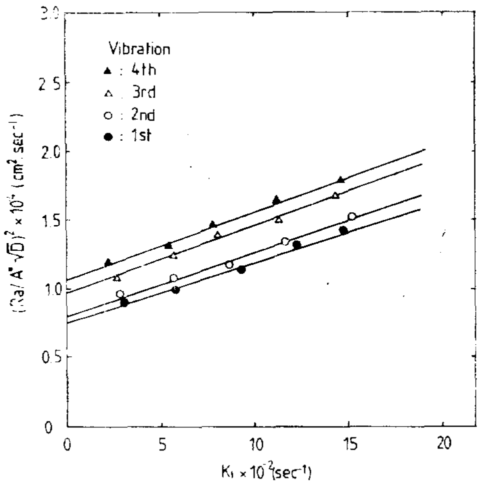


Fig. 8. Danckwerts plots in the packed-vibration system at U_g=10.4

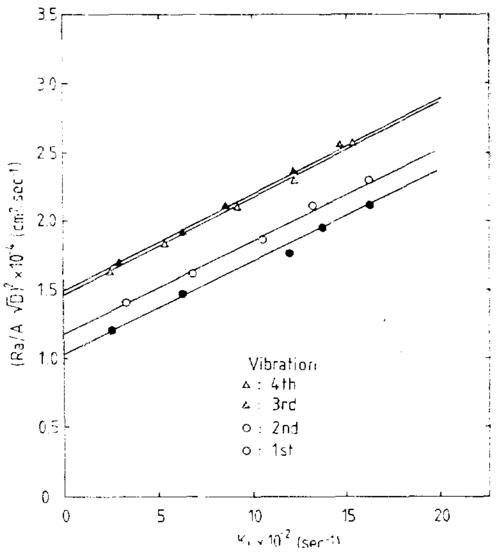


Fig. 9. Dackwerts plots in the packed-vibration system at U_g=15.6

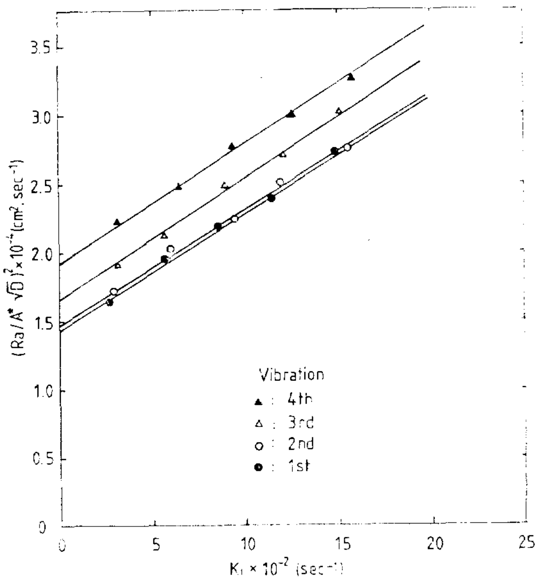


Fig. 10. Danckwerts plots in the packed-vibration system at U_g=20.8

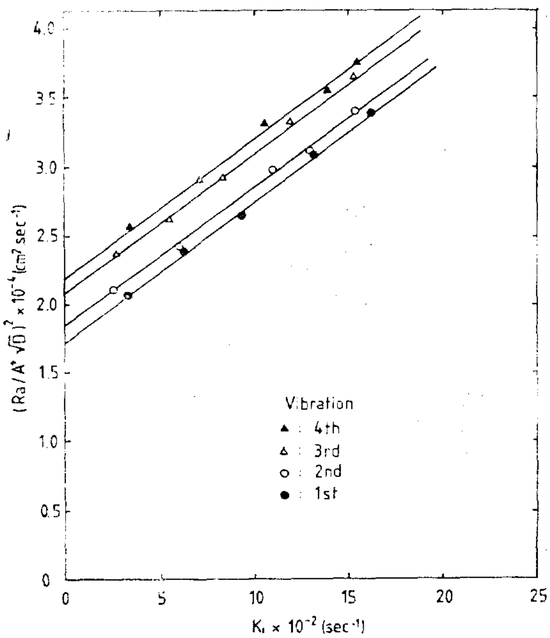


Fig. 11. Danckwerts plots in the packed-vibration system at U_g =24.2

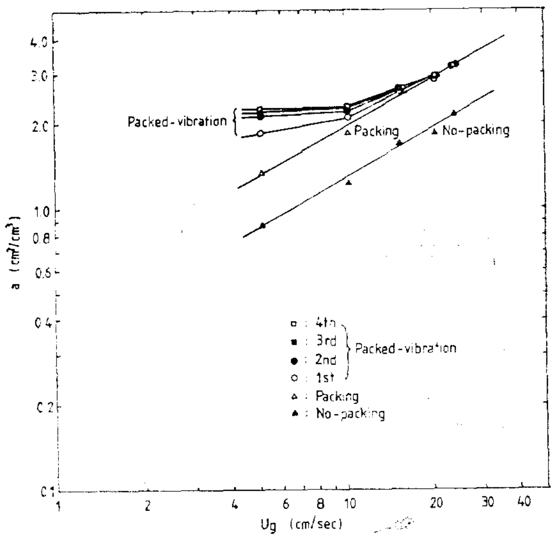


Fig. 12. Relationship between gas-liquid interfacial area and superficial gas velocity in the system of no-packing, packing, and packed-vibration

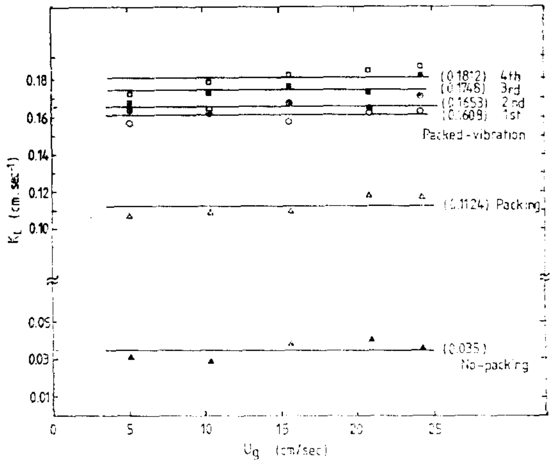


Fig. 13. Relationship between mass transfer coefficient (K_L) and superficial gas velocity in the system of no-packing, packing, and packed-vibration

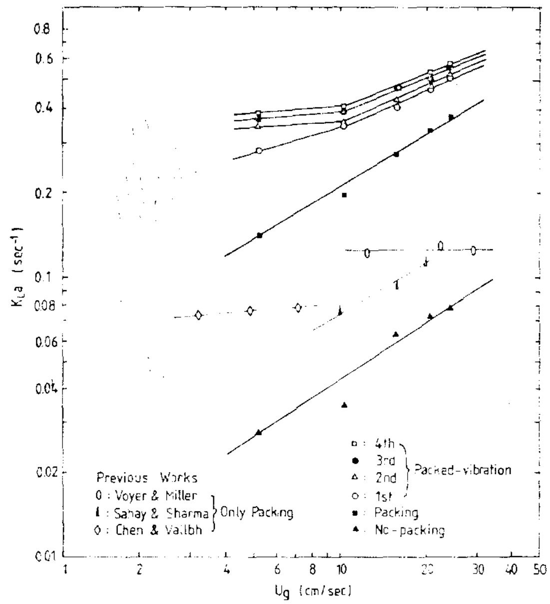


Fig. 14. Relationship between volumetric mass transfer coefficient and superficial gas velocity in the system of no-packing, packing and packed vibration.

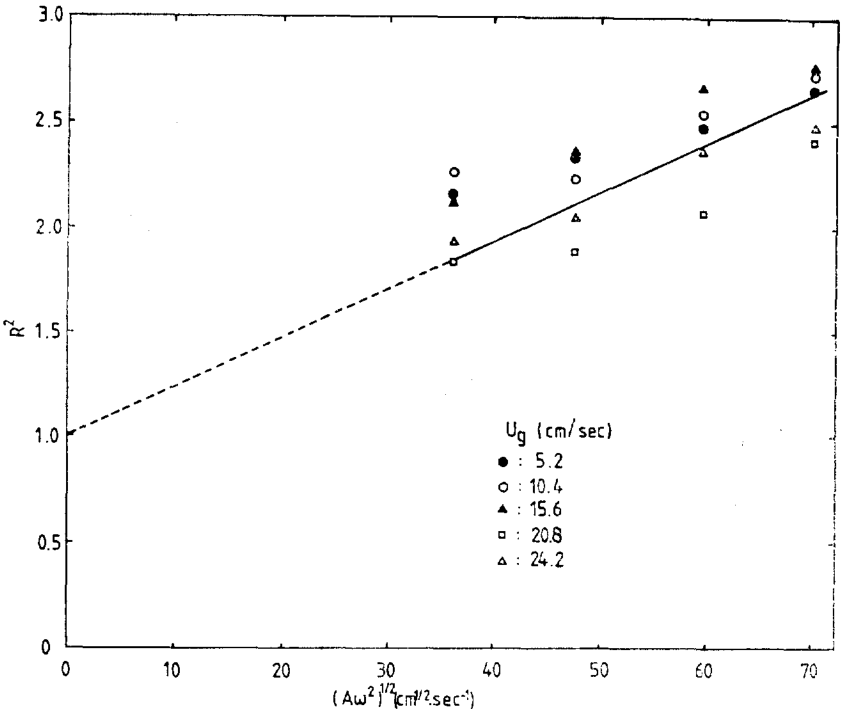


Fig. 15. Comparison of Experimental data with Eq. 16

Acknowledgements

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Nomenclature

- a Interfacial area per unit volume, cm^{-1}
- A Amplitude of liquid vibration, cm
- A^* Concentration of dissolved gas at interface, g mole/cm^3
- B $(A\omega^2)$ at the interface/$(A\omega^2)$ in the bulk, correction factor
- C Numerical constant
- D Molecular diffusivity, cm^2/sec
- D_E Eddy diffusivity, cm^2/sec
- f Frequency (Hz)
- h Mean head of bubble, $h'(1-\phi)$, cm
- h' aerated liquid height from bubble to top of column, cm
- h_0 Location of overflow line, cm
- K_1 First-order rate constant, sec^{-1} (from Pohorecki, R., Chem. Eng. Sci., 23, 1447 (1968).)
- K_L Liquid side mass transfer coefficient, cm/sec (from intercept of the Danckwerts rate equation)
- $K_{L,V}$ Liquid side mass transfer coefficient, cm/sec (from intercept of the Danckwerts rate equation with vibration)
- $K_{L,P}$ Liquid side mass transfer coefficient, cm/sec (from intercept of the Danckwerts rate equation without vibration (only packing))
- P_0 Pressure applied to liquid surface, dyne/cm^2
- P_s Pressure at the surface of bubble, dyne/cm^2
- P_s' Turbulent fluctuation pressure at the surface of bubble, dyne/cm^2
- $\tilde{P}_s'$ $[(\bar{P}_s')^2]^{1/2}$ dyne/cm^2

$\tilde{P}_l'$ Turbulent fluctuation pressure on the gas bubble interface

Q Overflowed quantity of water at location h_0, cm^3

R $K_{L,V}/K_{L,P}$, dimensionless

R Rate of absorption per unit area of surface after contact time, g-mole/cm^2·sec

S Cross-sectional area of column, cm^2

t Time, sec

U_g Superficial gas velocity, cm/sec

$\bar{U}_r$ Rising velocity of bubble, cm/sec

V_0 Characteristic turbulence velocity defined by $V_0 = \left(\frac{\tau_0}{\rho}\right)^{1/2}$, cm/sec

$\tilde{V}_{x,y}$ Fluctuation velocity in x-direction or y-direction, cm/sec

$\tilde{V}_v'$ Root mean square fluctuation velocity at the interface due to vibration in the liquid phase, cm/sec

$\bar{V}_0$ Volumetric gas flow rate at 24°C, 1 atm. cm^3/sec

x Distance along direction parallel to the interface of bubble, cm

y Distance perpendicular from interface of bubble, cm

Greek symbols

δ Thickness of equivalent diffusion sublayer, cm

λ Thickness of zone of damped turbulence near gas-liquid interface, cm

ρ Liquid density, g/cm^3

σ Surface tension of liquid, dyne/cm

τ_0 Tangential stress exerted on surface, g/cm·sec^2

ϕ Gas holdup, dimensionless

$\phi(x)$ Function of x

ω Circular frequency $(2\pi f)$, rad/sec

Overbars

— time average value

~ root mean square

′ fluctuation

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