

MEASUREMENT OF INTERFACIAL AREA AND INTENSITY OF MASS TRANSFER IN THE GAS PHASE IN A PACKING WITH SIGNIFICANT DEPENDENCE OF THE INTERFACIAL AREA ON THE DENSITY OF IRRIGATION

Jan ČERVENKA, Zdeněk BROŽ and Václav KOLÁŘ

*Institute of Chemical Process Fundamentals,
Czechoslovak Academy of Sciences, 165 02 Prague 6 - Suchbát*

Received November 2nd, 1982

The dependence has been measured of the interfacial area and the number of transfer units for gas side resistance controlled absorption on the flow rate of gas and liquid at counter- and co-current flow arrangement. The measurements have been carried out for a vertical expanded metal sheet packing exhibiting a strong dependence of the interfacial area on the density of irrigation. The interfacial area has been measured by absorption of carbon dioxide into a solution of sodium hydroxide under the conditions of the pseudo first order reaction. The number of transfer units has been measured by absorption of sulphur dioxide also into a solution of sodium hydroxide. In addition, the pressure drop has been correlated against the flow rate of gas and liquid.

The vertical expanded metal sheet packing for mass and heat transfer columns consists of a bunch of parallel sheets of expanded metal suspended on a special liquid distributor. Under the two phase flow of gas and liquid the liquid trickles down the surface of the sheets and the gas streams in the channels between the sheets. At low irrigation rates the liquid trickles only along the ribs of the expanded metal sheets while at higher irrigation rates covers also the mesh of the sheets. Increasing flow rate of liquid thus considerably alters the geometry of the flow channel available for the gas. This alters also the hydrodynamic characteristics of the channel. The expanded metal sheets ensure stable favourable distribution of liquid on the sheets and its intensive mixing. The spatial structure of the expanded metal sheets enhances the turbulence of the gas phase.

The problems of mass transfer during absorption with predominantly gas side resistance in an apparatus with a vertical packing made of expanded metal sheet has been investigated earlier by Lacina¹. This author measured absorption of ammonia into water in a column of rectangular cross section with 2 m long packed section using various types of expanded metal sheet and various spacing of the sheets. For part of the results, obtained under the conditions to be expected in absorbers (about 12 mm spacing of the sheets and the 16 × 6 mm mesh size of the expanded metal sheets), the experiments were supplemented by the data on the interfacial area² for the same experimental set-up. The interfacial area was measured under the conditions of the

pseudo first order reaction for absorption of carbon dioxide into a water solution of sodium hydroxide. Apart from that also the interfacial area was evaluated from the results of measurement of absorption of ammonia by using an earlier published³ model of heat and mass transfer into a turbulently flowing phase. The evaluation was made on the basis of parameters of the model obtained from a single phase flow through a tube of circular cross section. Independently obtained interfacial areas were found to give a good agreement.

Additional orientational heat and mass transfer experiments for systems with predominantly gas side resistance (adiabatic evaporation, absorption of sulphur dioxide into a solution of sodium hydroxide) suggested that the conclusions of the previous papers^{1,2} are not valid generally. The cause apparently rests in the inappropriate use of the ammonia–water system for the study of absorption with gas side resistance control. In order to have a measurable concentration of ammonia in the exit stream from the column (for the given number of transfer units $N_{OG} = 4-7$), the inlet concentration had to be high (15 to 30%), hence the absorbed amount was large and the absorption was accompanied by evolution of a significant amount of heat. In addition, the absorption was affected also by the conditions at the interface. For instance, the onset of loading of liquid in the packing occurs during absorption of ammonia at significantly higher flow rates (by 20 to 30%) compared to the rates of an inert gas alone. At the same flow rate of liquid thus the interfacial area need not be generally the same during absorption and the measurements of the interfacial surface by chemical methods.

The aim of this work has been to obtain by a suitable choice of systems experimental data on the extent of interfacial surface area and number of transfer units during absorption free of the above mentioned shortcomings. For the measurement of the absorption under the gas side resistance control we took absorption of sulphur dioxide into a water solution of sodium hydroxide. The advantages of this system are following: 1) The resistance to mass transfer in the liquid phase is negligible. 2) The properties of the liquid phase for absorption and for measurement of the interfacial area are nearly identical. In both cases the liquid phase is a solution of sodium hydroxide with some sodium sulphite or sodium carbonate appearing due to the chemical reaction in the solution. 3) The analytical method employed permitted measurement of low concentrations of sulphur dioxide in the gas phase.

In order to restrict the influence of the liberated heat of the reaction on the process, the column, in contrast to the previous paper¹, was shortened to 0.95 m (to $N_{OG} = 2-3.5$). This modification, together with the system sulphur dioxide–water solution of sodium hydroxide, permitted the amount of the absorbed gas to be decreased by almost three orders of magnitude.

A drawback of the shortened column is the relative increase of the entrance and the outlet section and their effect on the experimental number of transfer units, interfacial area and pressure drop. For this reason still additional series of measurements have been carried out in a 0.35 m long column with identical inlet and outlet section as those used in the 0.95 m column. By subtraction the values of the investigated quantities for both columns data are obtained that correspond better to the conditions in the channel between the sheets of the packing.

In addition to the experiments with the counter-current flow arrangement it has been decided to carry out also measurements under the cocurrent flow. Aside from

the practical reasons we were lead to this decision also by the expectation that information important for the analysis and description of the phenomena within the packing should be obtained.

EXPERIMENTAL

Experimental set-up. The experimental set-up is shown schematically in Fig. 1. The column is of rectangular cross section 103×70.5 mm 830 or 230 mm long. At both ends the column was equipped with larger cylindrical chambers 150 mm in diameter. The length of the packing between the lower edge of the supporting liquid distributor in the upper chamber and the level of liquid in the bottom chamber was 950 or 350 mm. At the bottom end the packing was submerged into the liquid in the bottom chamber. The packing proper consisted of six sheets of expanded metal with the 16×6 mm mesh size. The spacing of the sheets was 11.75 mm. The liquid in the storage tank was thermostated to $20 \pm 0.5^\circ\text{C}$.

The inlet air was saturated by water vapours in the humidifying column and at the same time thermostated to $20 \pm 1^\circ\text{C}$. The humidified air was mixed with the absorbant gas in a mixer and the mixture entered, under the cocurrent flow arrangement, into the upper, or, under the counter-current flow, into the lower column chamber.

Measured quantities. Apart from the flow rate of gas, measured by an orifice made according to VDI (ref.⁴), and the flow rate of liquid, measured by a rotameter, the additional measured

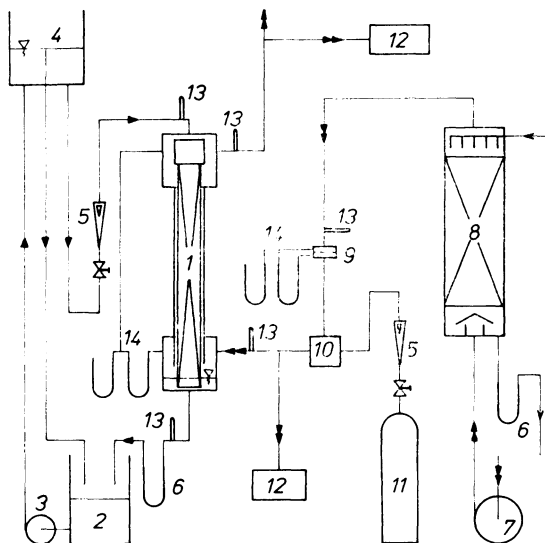


FIG. 1

Sketch of the set-up. 1 absorption column with vertical expanded metal sheets packing, 2 liquid storage tank, 3 pump, 4 overflow tank, 5 rotameter, 6 syphon, 7 blower, 8 humidifying column, 9 orifice, 10 mixer, 11 pressure cylinder, 12 gas analyser, 13 thermometer, 14 manometer

quantities were the temperatures of both streams at the inlet and the outlet of the column, absolute pressure in the column head and necessary data on composition of the phases. The pressure losses were tapped through pressure ports located in both chambers and measured by a micro-manometer.

During experiments measuring the interfacial surface the concentration of carbon dioxide (at the inlet 1.5–2%) was measured in both streams by a Zeiss interferometer. The gas from the sampling point passed through a U-tube filled with silicagel to the suction end of a membrane pump further *via* a regulating valve to 1 m long kyvette of the interferometer. The connection was made of copper tubing of small cross section. The reason was that the time for steadying down with the use of a plastic or a rubber tubing was much too long apparently due to the sorption effects on the walls of the tubing. The concentration of the sodium hydroxide (initial concentration 0.5 kmol/m³) and sodium carbonate was analyzed by titration following Warder. Replacement of the sodium hydroxide solution was carried always after its concentration in the tank had dropped below 0.3 kmol/m³.

During measurement of absorption with gas side resistance control the concentration of SO₂ (inlet concentration 0.015 to 0.05%) was measured by a method proposed by Hochheiser⁵.

Experimental conditions. The superficial velocity of gas in the column was varied in the range between 0.7 and 3.5 m/s for the counter-current and up to 3.8 m/s for the cocurrent flow. The upper limit of the velocity was limited by the capacity of the air pump. For a selected flow rate of liquid the measurement encompassed about six to eight gas rates from the above range. Nine different liquid mass velocities were investigated from 1.35 to 25 kg/sm². Corresponding densities of irrigation per unit length of the irrigated edge of the packing were 0.0165 and 0.307 kg/sm. The measurements necessary for the determination of the interfacial area and the number of transfer units for absorption in the above range of rates were carried out for both the longer (0.95 m) and the shorter (0.35 m) column in the co- and counter-current flow arrangement.

Data processing. The extent of the interfacial surface between the liquid and the gas exposed in the expanded metal sheet packing, on the walls of the column, in the distributor of liquid and on the level of the liquid in the bottom chamber were measured experimentally under the conditions of the pseudo first order reaction⁷. Carbon dioxide was absorbed from a mixture with air into the circulating solution of sodium hydroxide.

The absorbed amount of carbon dioxide, G , was assessed from the concentration difference of CO₂ in the inlet and the outlet and the flow rate of the gas mixture and is given by the following equation

$$G = Ac_A(k_{OH}c_{OH}D_A)^{1/2}. \quad (I)$$

Owing to the small height of the packed section and the small changes of composition of the gas and the liquid phase, all quantities in Eq. (I) were substituted as arithmetic means of the values at the inlet and the outlet end. The solubility of carbon dioxide in liquid at the given temperature and partial pressure was computed from the Henry law. An expression published by Danckwerts and Sharma⁶ was used to evaluate the Henry constant, while taking corrections on the presence of the hydroxide and carbonate from the Danckwerts' monograph⁷. From the same monograph we took over the equation for the second order reaction rate constant k_{OH}^0 at infinite dilution

$$\log k_{OH}^0 = 10.635 - 2.895/T.$$

The effect of the ionic strength of the solution on the reaction rate constant

$$\log (k_{OH}/k_{OH}^0) = 1.33 \cdot 10^{-4} I$$

was evaluated from Fig. 10 presented in the paper of Nijsing, Hendriksz and Kramers⁸ while taking for I

$$I = c_{\text{OH}} + 3c_{\text{CO}_2}.$$

The diffusivity of carbon dioxide in the solution was corrected on temperature and viscosity according to

$$D_A \mu_L / T = \text{const.}$$

following from the equation proposed by Wilke and Chang⁹. For the diffusivity of CO_2 in water at 25°C we took value¹⁰

$$D_A = 1.92 \cdot 10^{-9} \text{ m}^2 \text{ s}^{-1}.$$

The difference of the interfacial area A for the 0.95 m and 0.35 m columns, related to a unit volume of the column, corresponding to a 0.6 m high section, represents the resulting interfacial area per unit volume of the column a .

The number of transfer units for absorption of SO_2 into the NaOH solution was evaluated from

$$N_{\text{OG}} = \ln (y_{\text{in}}/y_{\text{out}}),$$

where y_{in} and y_{out} are mole fractions of SO_2 at the column inlet and the outlet. The difference between N_{OG} values for the longer and the shorter column, related to the height of 0.6 m, represents N_{OG}/h . Analogously we proceeded in the evaluation of $\Delta p/h$. The values of A , N_{OG} , Δp for the shorter column were subtracted from the graphically smoothed dependences of these quantities on the flow rate of gas for various irrigation rates.

RESULTS

Pressure Drop

Averaged values of the pressure drop, obtained as part of the measurement of the interfacial area and as part of the SO_2 absorption measurements, are plotted in Fig. 2 in dependence on the flow rate of liquid for various gas rates. A comparison of these values with the earlier data^{11,12} in a column of circular cross section 108 mm in diameter showed that the pressure drop in the rectangular column is by about 60 to 110% higher. The cause for this observation rests apparently in the fact that in the column of circular cross section there was an empty space left between the packing and the wall of the column exhibiting a lower resistance than the channel between the sheets. In order to make the pressure drop across the packing the same as that across the empty space, the velocity of gas in the packing has to be lower. The fraction of the column cross section left empty between the packing and the wall in case of the small column is relatively large (here about 20%). The true gas velocity in the packing for the small column of circular cross section is then probably significantly lower than the mean velocity to which the observed pressure drop was ascribed. In the column of rectangular cross section the above shortcoming has been suppres-

sed and the pressure drop of the rectangular cross section, even though small, corresponds to large scale columns¹³.

Under the two phase flow of gas and liquid only part of the energy lost by the gas upon passing through the column is being dissipated in the gas phase. Another part is passed onto the liquid to be dissipated here. Commonly in plate columns and in case of strong gas/liquid interactions in packed beds, part of the energy is used up to create new gas/liquid interfacial area. From this standpoint it is logical to divide the overall pressure losses to those corresponding to the energy dissipated by gas phase friction, Δp_G , and the energy transferred to the liquid, Δp_L .

$$\Delta p = \Delta p_G + \Delta p_L . \quad (2)$$

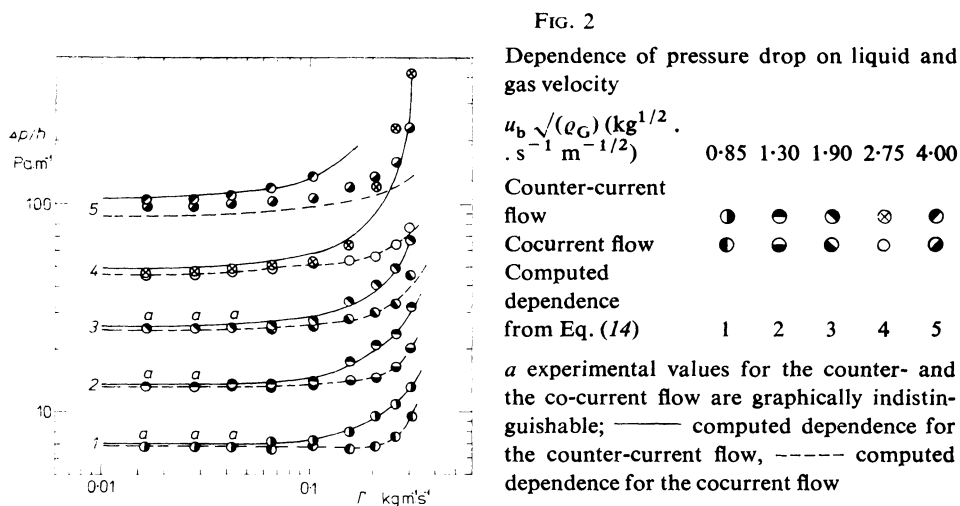
The term Δp_L becomes manifest through the change of the hold-up (increased under the counter-current and decreased under the cocurrent flow) in comparison with the hold-up of liquid unaffected by the flow of gas.

$$\Delta p_L = \pm a_0(z - z_0)gh/2 . \quad (3)$$

Here and in the following cases the upper sign holds for the counter-current flow, while the lower sign is valid for cocurrent flow.

For the hold-up of liquid in the above cited papers^{11,12} the following relationship was obtained based on the modified Nusselt's theory

$$\Gamma \varrho_L \mu_L = \varphi z^3 \mp \psi(\Delta p/h) z^2/a_0 . \quad (4)$$



For zero pressure drop this expression reduces to

$$\Gamma \varrho_L \mu_L = \varphi z_0^3. \quad (5)$$

The parameter ψ should, according to the theory, depend on the true interfacial area, which, however, was not measured. The use of the mean value for the description of the dependence of the liquid hold-up on gas velocity and liquid velocity lead to considerable deviations of the measured and computed values of the hold-up. For the correlation we therefore used a modified relation for the counter-current flow¹¹

$$\Gamma \varrho_L \mu_L = \varphi z^3 - b_1 [(\Delta p/h)] z^2/a_0]^{b_2}. \quad (6)$$

Values of the parameters φ , b_1 , b_2 are different for different types of the expanded metal sheet but independent of the spacing of the sheets. A good agreement has been found between experimental hold-ups and those computed from the correlation (6).

Use of Eq. (6) is somewhat controversial outside the range of the conditions for which it had been obtained. For the evaluation of the term Δp_L we had to extrapolate into the region of lower irrigation rates, higher pressure drops and, in addition, to the case of the cocurrent flow. The theoretically founded expression (4) was therefore again applied to the set of experimental data from the original work¹¹. For the experiments with the 16×6 mm expanded metal sheets and the spacing 12.5 mm we used the original value of the coefficient φ ($= 0.57 \text{ m/s}^2$) and computed the value of ψ . The obtained data on ψ , averaged for individual irrigation rates, are plotted in Fig. 3 in dependence on the density of irrigation. The experimental data were fitted to the curve of the dependence of ψ on Γ . The broken line shows ψ from the original paper¹¹, obtained by averaging even for various irrigation rates and various spacings of the sheets.

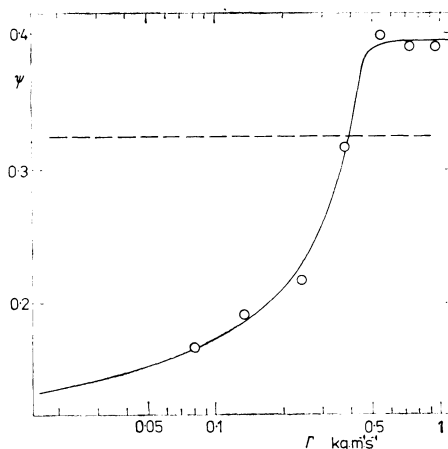


FIG. 3

Plot of the coefficient ψ versus the density of irrigation \circ from experimental data¹¹.
 — estimated dependence $\psi = \psi(\Gamma)$,
 ---- average value of ψ for 16×6 mm expanded metal sheets and various spacings of the sheets from the previous paper¹¹

For the calculation of Δp_L one can thus use Eqs (3), (4) and (5) after substituting into Eq. (4) the coefficient ψ read off the graphical dependence in Fig. 3. The pressure drop corresponding to the energy dissipated by friction in the gas phase, Δp_G , can be computed from the overall pressure drop by using Eq. (2).

For the correlation of Δp_G as suitable appears the equation of Fanning's type

$$\Delta p_G = \xi(h/d_c)(u_r^2/2)\varrho_G, \quad (7)$$

where the characteristics length scale of the channel between the sheets is

$$d_c = 2Pe \quad (8)$$

and the relative velocity of gas in the channel is

$$u_r = u_b/e \pm v_L. \quad (9)$$

The void fraction e represents the void fraction of the column with the dry packing decreased by the fraction of the column cross section occupied by liquid.

$$e = 0.97 - za_0/(2\varrho_L). \quad (10)$$

In the previous papers^{11,12} the effective surface velocity of liquid v_L was expressed using the assumption that the thickness of the liquid film is constant and that the surface of the film moves at the mean velocity of the film.

$$v_L = \Gamma/z. \quad (11)$$

From comparison of the pressure drop under the co- and counter-current flow, particularly at low irrigation rates, it is, however, apparent that the effect of v_L is substantially smaller than that corresponding to Eq. (11). The spatial protrusion of the ribs of the expanded metal sheets affects the resistance of the channel between the sheets so strongly as to suppress the effect of the direction of the flow with respect to the liquid on the relative velocity of gas, u_r .

In further work the effective surface velocity of liquid was taken to be an empirical parameter. For the evaluation the following assumptions were used: 1) The coefficient of resistance ξ is the same for the co- and counter-current flow, provided that the value of the relative Reynolds number, Re_{Gr} , and the flow rate of liquid are the same, and depends solely on these quantities. 2) The effective velocity of liquid surface is independent of gas velocity.

These assumptions are acceptable in the region of low gas/liquid interactions. Their validity in the proximity of the flooding point, however, is rather dubious. As a first approximation the dependence of the friction coefficient on the Reynolds number was taken in the form of a power function $\xi = b Re_{Gr}^{-0.25}$, where b depends only on the flow rate of liquid. In accordance with the assumption 1 one obtained

from Eq. (7) the following expression for v_L

$$[\Delta p_G e^3 / (u_b + v_L e)^{1.75}]_{\text{counter-current}} - [\Delta p_G e^3 / (u_b - v_L e)^{1.75}]_{\text{cocurrent}} = 0. \quad (12)$$

For the chosen velocity of gas (from the values $u_b \sqrt{\rho_G} = 0.8; 1.3; 1.9 \text{ kg}^{1/2} \text{ s}^{-1} \cdot \text{m}^{-1/2}$) and the corresponding pair of Δp_G for the counter- and cocurrent flow the value of v_L was computed. The dependence of v_L on the velocity of gas in the above range of gas velocities was not detected. The average values of v_L for individual flow rates of liquid are shown in Fig. 4. The full line shows the dependence of v_L on Γ computed from Eq. (11) for $z = z_0$. The broken line represents the estimate fitted to the experimental values v_L .

The values of the resistance coefficient according to Eq. (7) were computed from the experimental data by using smoothed values v_L (broken line in Fig. 4). For the correlation of the resistance coefficient an equation of the Ergun type proved useful

$$\xi = b_3 / Re_{Gr} + b_4. \quad (13)$$

The parameters b_3 and b_4 depend on the flow rate of liquid

$$b_3 = 190 - 241 \Gamma^{0.4}, \\ b_4 = 0.135 - 0.05 \Gamma^{0.4}.$$

With increasing flow rate of liquid b_3 and b_4 decrease. This well agrees with the concept of diminishing "roughness" of the walls of the channel between the sheets of the expanded metal with increasing flow rate of liquid.

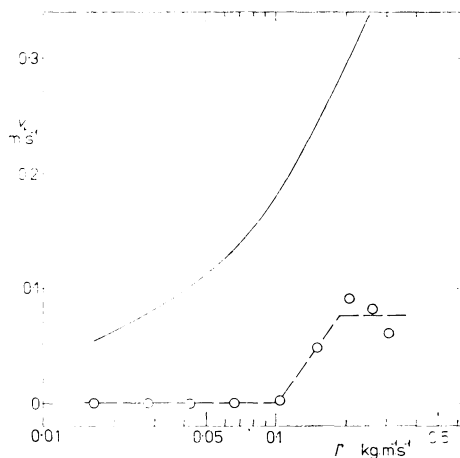


FIG. 4

Plot of the effective surface velocity of liquid versus density of irrigation. \circ computed from experimental data using Eq. (12), — dependence computed from Eq. (11) for $z = z_0$, ---- estimated course from experimental values

Eq. (1) thus takes the form

$$\Delta p = (b_3/Re_{Gr} + b_4) (h/d_e) (u_r^2 \rho_G/2) \pm a_0(z - z_0) gh/2. \quad (14)$$

The hold-up of liquid, z , however, must be computed from Eq. (4) which contains also the pressure drop. The calculation can be carried out by successive approximation. The computed dependences are shown in Fig. 2. These dependences agree well with the experimental data except for the neighbourhood of the flooding point.

Interfacial Area

The dependence of the interfacial area on the flow rate of gas at constant flow rate of liquid was found only in region above the loading point. In the experimentally investigated range of gas rates at counter-current flow this occurred for the densities of irrigation $\Gamma \geq 0.104$ kg/sm. The curves fitted to the experimental data and for higher liquid rates are shown in Fig. 5. An increase of the interfacial area was observed at cocurrent flow arrangement for the maximum liquid rates ($\Gamma = 0.208$; 0.260 ; 0.307 kg/s m) at gas velocities from 3.5 to 3.8 m/s, namely by 15 to 30% . Otherwise no effect of gas flow rate on the interfacial area was observed for the cocurrent flow arrangement.

The dependence of the extent of the interfacial surface on the flow rate of liquid for both the cocurrent and the counter-current flow arrangement is depicted in Fig. 6. Experimental data in this figure represent the average from the region below the loading. The interfacial area increases with increasing flow rate of liquid. From the

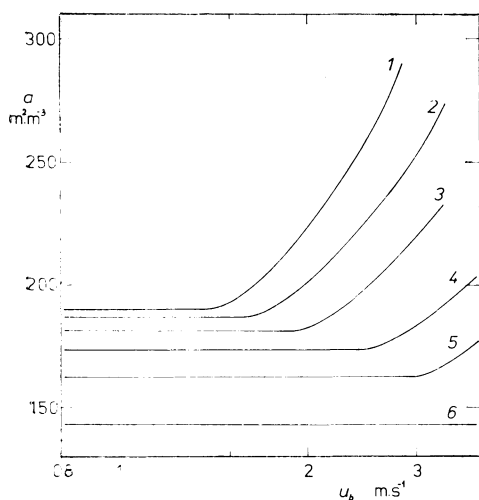


FIG. 5

Plot of interfacial area *versus* gas velocity for various liquid rates at counter-current flow.
 1 $\Gamma = 0.307$ kg/sm; 2 $\Gamma = 0.260$ kg/sm;
 3 $\Gamma = 0.208$ kg/sm; 4 $\Gamma = 0.156$ kg/sm;
 5 $\Gamma = 0.104$ kg/sm; 6 $\Gamma = 0.066$ kg/sm

density of irrigation from 0.104 to 0.156 kg/sm, when the majority of the mesh openings of the expanded metal sheet is covered by the liquid film, the growth is slow. The differences for the co- and counter-current flow are small. The finding that for seven out of nine pairs the interfacial areas for the cocurrent flow is greater is probably insignificant. The figure shows also some interesting geometrical characteristics of the column: the surface of the ribs of the expanded metal sheet, specific surface of the packing, a_0 and the same quantity increased by the surface of the column walls. The results of measurements correspond also to the results of visual observation showing that in case of high flow rates the liquid irrigates partially also the walls of the column.

The dependence of the interfacial area on the flow rate of liquid can be correlated by the expression¹⁴

$$a = b_5 - (b_5 - b_6) \exp(-b_7 \Gamma), \quad (15)$$

where $b_5 = 188 \text{ m}^2/\text{m}^3$, $b_6 = 27 \text{ m}^2/\text{m}^3$, $b_7 = 18.6 \text{ ms/kg}$. The dependence according to Eq. (15) is shown in Fig. 6 by the solid line.

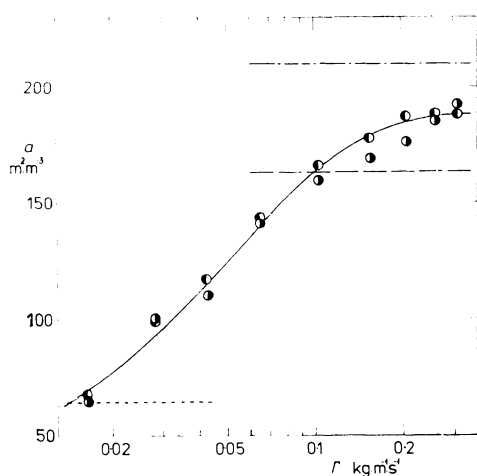


FIG. 6

Specific interfacial area in region below the loading point; ● cocurrent flow, ○ counter-current flow, - - - - - all built-in surface including column walls, - - - - - surface area of the packing a_0 , ····· surface of the ribs of the expanded metal sheet, ——— dependence according to Eq. (15)

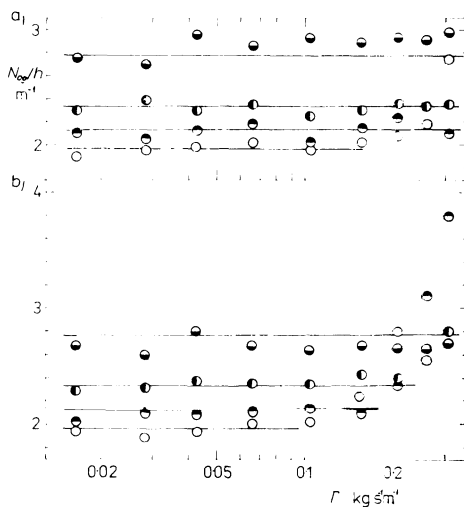


FIG. 7

The number of transfer units as a function of liquid and gas rates

a) cocurrent flow b) counter-current flow

● $u_g = 0.8 \text{ m/s}$; ◐ $u_g = 1.7 \text{ m/s}$; ○ $u_g = 2.5 \text{ m/s}$; ○ $u_g = 3.5 \text{ m/s}$

The Number of Transfer Units

The dependence of the number of transfer units on the flow rate of liquid for different gas velocities is shown in Fig. 7. According to the experimental results the number of transfer units for the region below the loading point is independent of the flow rate of liquid and decreases with the flow rate of gas. In region above the loading and the counter-current flow of phases the number of transfer units increases with increasing flow rate of both liquid and gas. For the cocurrent flow arrangement the increased number of the transfer units appears only for the maximum gas velocities 3.5 to 3.8 m/s and for the highest densities of irrigation (for $\Gamma = 0.307$ kg/sm by about 35%). In region below the loading the differences between N_{OG} for the counter- and co-current flows are insignificant. Only at the lowest gas velocities (0.7 to 0.9 m/s) is the average value of N_{OG} for the cocurrent flow by about 5% higher than for the counter-current flow.

The number of transfer units in region prior to the onset of the loading can be correlated, for the given system and packing, by the relationship

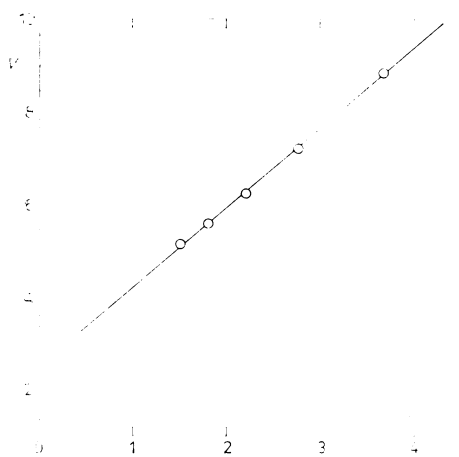


FIG. 8

Correlation of the loading point

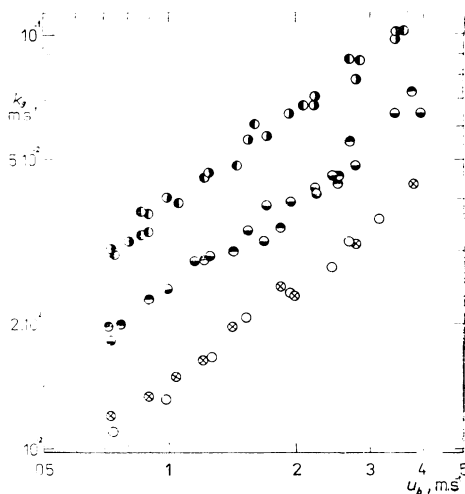


FIG. 9

The gas side mass transfer coefficient as a function of gas velocity

(kg/sm)	0.0165	0.0425	0.208
Cocurrent flow	●	●	○
Counter-current flow	●	●	○

$$N_{0G}/h = 2.63u_b^{-0.23}. \quad (16)$$

The values computed from Eq. (16) are shown in Fig. 7 by solid lines.

The Onset of Loading

The onset of loading is the state when an observable effect of the counter-currently flowing gas phase on the flowing liquid appears. At constant flow rate of liquid this becomes manifest on the changed character of the plot of the pressure drop, the number of transfer units and the interfacial area *versus* the gas velocity. Introduction of the notion of the loading point has only practical significance for in reality the above changes are continuous.

The "experimental" value of the onset of loading for a given flow rate of liquid was obtained in such a manner that the gas velocity was estimated for which a change of the character appeared on the plots $\Delta p(u_b)$, $a(u_b)$ and $N_{0G}(u_b)$. The arithmetic average of the three values represents the gas velocity of the loading point. For the irrigation rates less than 0.104 kg/ms no loading point was detected in the experimentally investigated range of gas velocities.

The beginning of the loading was correlated by the earlier used expression¹² for the correlation of the flooding point

$$V = b_8 U + b_9, \quad (17)$$

where

$$U = [(Q_G/Q_L)^2 (\rho_L/\rho_G)]^{1/4}$$

$$V = \{2ge^3 \rho_L^2 d_c / [Q_L^2 (\mu_L/\mu_w)^{0.2}]\}^{1/4}$$

and $b_8 = 1.72$; $b_9 = 2.48$. A comparison of the "experimental" values of U and V with the correlation (17) is shown in Fig. 8.

The Gas Side Mass Transfer Coefficient

The dependence of the mass transfer coefficient k_G on the velocity of gas is shown in Fig. 9 for several liquid rates. The mass transfer coefficient is approximately proportional to $u_b^{0.77}$. Significant is the dependence of k_G on the density of irrigation for $\Gamma \lesssim 0.104$ kg/sm. With increasing liquid rate k_G diminishes. The plot of k_G does not exhibit the change at the onset of loading analogous to the change of the dependences of $a(u_b)$ and $N_{0G}(u_b)$. The change of the dependence of $N_{0G}(u_b)$ at the onset of loading is thus proportional to the change of the dependence $a(u_b)$.

LIST OF SYMBOLS

a	specific interfacial area (m^{-1})
a_0	specific surface of packing (twice the surface of the sheet per unit volume) (m^{-1})
A	interfacial area (m^2)
$b_1 - b_9$	coefficients in the correlations
c_A	concentration of CO_2 in liquid (mol/m^3)
c_{CO_3}	concentration of carbonate ions in liquid (mol/m^3)
c_{OH}	concentration of hydroxyl ions in liquid (mol/m^3)
d_e	equivalent diameter (m)
D_A	diffusivity of carbon dioxide in solution ($\text{m}^2 \text{s}^{-1}$)
e	void fraction
g	acceleration due to gravity (m s^{-2})
G	absorbed amount of carbon dioxide (mol/s)
h	height of packing (m)
I	ionic strength of solution (mol/m^3)
k_G	gas side mass transfer coefficient (m s^{-1})
k_{OH}	rate constant ($\text{m}^3 \text{mol}^{-1} \text{s}^{-1}$)
k_{OH}^0	rate constant at infinite dilution ($\text{m}^3 \text{mol}^{-1} \text{s}^{-1}$)
N_{OG}	number of transfer units related to the gas phase (—)
Δp	overall pressure drop (Pa)
Δp_G	pressure drop due to friction (Pa)
Δp_L	pressure drop of gas corresponding to energy transmitted to liquid (Pa)
P	spacing of sheets (m)
Re_{Gr}	relative Reynolds number in gas phase (—), $Re_{\text{Gr}} = u_r d_e / \nu_G$
Q_G	gas mass velocity ($\text{kg}/\text{m}^2 \text{s}$)
Q_L	liquid mass velocity ($\text{kg}/\text{m}^2 \text{s}$)
T	absolute temperature (K)
u_b	superficial velocity of gas (m/s)
u_r	relative gas velocity within the packing (m/s)
U	parameter in Eq. (17)
v_L	effective surface velocity of liquid (m/s)
V	parameter in Eq. (17)
y	mole fraction in gas phase (k mol of species/k mol of mixture)
z	hold-up related to 1 m^2 of expanded metal sheet (kg/m^2)
z_0	hold-up of liquid at $\Delta p = 0$ (kg/m^2)
Γ	mass rate of liquid per unit length of irrigated edge of packing (kg/sm)
μ_L	liquid viscosity ($\text{kg}/\text{m s}$)
μ_w	viscosity of water at 20°C ($\text{kg}/\text{m s}$)
ν_G	kinematic viscosity of gas (m^2/s)
ξ	coefficient of resistance in Eq. (7)
ρ_G	density of gas (kg/m^3)
ρ_L	density of liquid (kg/m^3)
ϕ	coefficient in Eq. (4) (m/s^2)
ψ	coefficient in Eq. (4) (—)

REFERENCES

1. Lacina J.: *Thesis*. Czechoslovak Academy of Sciences, Prague 1978.
2. Lacina J., Brož Z., Kolář V.: *This Journal* **45**, 457 (1980).
3. Kolář V.: *This Journal* **42**, 1310 (1977).
4. VDI-Durchfluß-Maßregeln, VDI-Verlag GMBH, Berlin 1943.
5. Chemical Analysis Vol. 29, *The Analytical Chemistry of Sulfur and its Compounds*, (Karchmer J. H., Ed.), Part I, p. 164. Wiley, New York 1970.
6. Danckwerts P. V., Sharma M. M.: *The Chemical Engineer*, CE 244, October 1966.
7. Danckwerts P. V.: *Reakce v soustavě plyn-kapalina*. Published by SNTL, Prague 1975 (Czech translation).
8. Nijssing A. R. T. O., Hendriksz R. H., Kramers H.: *Chem. Eng. Sci.* **19**, 88 (1959).
9. Wilke C. R., Chang P.: *A.I.Ch.E.J.* **1**, 264 (1955).
10. Himmelblau D. M., Ferrell R. T.: *A.I.Ch.E.J.* **13**, 702 (1967).
11. Tesař A.: *Thesis*. Czechoslovak Academy of Sciences, Prague 1976.
12. Tesař A., Kolář V.: *This Journal* **42**, 3301 (1977).
13. Červenka J., Kolář V., Novotný M., Grym I.: *Chem. Prům.*, 32/57, 622 (1982).
14. Brož Z., Endršt M.: *This Journal* **45**, 3089 (1980).

Translated by V. Staněk.