THE GAS-SIDE MASS TRANSFER COEFFICIENT AND THE INTERFACIAL AREA UNDER THE TURBULENT FLOW OVER THE PACKING OF PARALLEL EXPANDED METAL SHEETS

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Specific interfacial area has been computed from experimental values of the gas-side volume mass transfer coefficient, $k_g a$, and the theoretically derived expressions for gas-side mass transfer coefficient per unit area of interfacial surface, k_g. The results have been compared with the specific interfacial area determined experimentally using the chemical method.

In one of the earlier papers[1] a theoretical model has been published of the mechanism of heat and mass transfer in a turbulent phase. This model respects the existence of three known hydrodynamic regions, *i.e.* the laminar layer, the transition region and the region of developed turbulence. In the expression for the mass transfer coefficient or heat transfer coefficient individual regions have been characterized by length scales δ_l, λ_p, λ_t. The validity of the presented model has been tested in a wide interval of variables in application to heat transfer in a circular tube where the necessary hydrodynamic parameters have been known. The process of testing consisted of taking two different values of the Prandtl criterion and known values of the heat transfer coefficients to calculate the parameters δ_l^+ and λ_p^+ and compare them with the known data from hydrodynamic studies. The agreement found was very good.

In the following paper the above model was applied to the absorption under the two-phase counter-current flow over the packing of expanded metal sheets which differ by their hydrodynamics significantly from the single-phase flow in a tube of circular cross section. In the given case one had to determine the magnitude of the interfacial area which significantly varies with the density of irrigation of the packing.

THEORETICAL

The mass transfer coefficient according to the mentioned model[1] is given by the following expression

$$k = D\,F(v/D)/[\delta_l\,F(v/D) + \lambda_p + \lambda_t\,\Phi(v/D)]\,. \qquad (1)$$

This expression may be arranged using following equations

$$u^* \delta_1/v = \delta_1^+(a)\,; \quad u^* \lambda_p/v = \lambda_p^+(b)\,; \quad \lambda_t = (v^3/\varepsilon)^{1/4}\,(c) \qquad (2a,b,c)$$

to get

$$k = [F(v/D)/(v/D)]\, u^*/[\delta_1^+ F(v/D) + \lambda_p^+ + (u^*/(\varepsilon v)^{1/4})\, \Phi(v/D)] \qquad (3)$$

or by substituting from the following equations

$$u^* = u_b (f/2)^{1/2}\,(a)\,; \quad f/2 = (1/4)\,(\Delta p d_e)/(L\varrho u_b^2)\,(b)\,;$$
$$\varepsilon = (\Delta p u_b)/(L\varrho e)\,(c) \qquad (4a,b,c)$$

into Eq. (3) to obtain

$$k = [F(v/D)/(v/D)]\, [(\Delta p d_e)/(L\varrho)]^{1/2}/\{2(\delta_1^+ F(v/D) + \lambda_p^+) +$$
$$+ [(\Delta p d_e^2 e)/(L\varrho u_b v)]^{1/4}\, \Phi(v/D)\}\,. \qquad (5)$$

On multiplying Eq. (5) by the specific surface area of the packing -a- a volume mass transfer coefficient ka is obtained which is readily available through experiments.

EXPERIMENTAL

To verify the validity of Eq. (1) the mass transfer under the two-phase counter-current flow between the liquid film flowing down the vertical sheets of expanded metal and the turbulent gas was chosen. The absorption was that of ammonia from air into water, *i.e.* a system characteristic by its low resistance in the liquid phase. As follows from Eq. (5) the experimental work requires also measurement of pressure drop across the effective part of the packing.

Apparatus. The scheme of the apparatus is sketched in Fig. 1. The effective part of the column 1 was of rectangular 103 × 70·5 mm cross section and 2000 mm long. The sheets of the expanded metal were suspended from below the liquid distributor. In the entrance and the exit region of the effective length of the packing there were ports for sampling pressure and drawing samples of gas and liquid. The liquid phase (water) was supplied by a pump 16 from the tank 2 into the overflow tank 3 from where the liquid proceeded by gravity to the liquid distributor. The flow rate of liquid was measured by orifices 5 or a rotameter 4. The liquid drained from the column into the siphon and the sewage pipe. Before entering the column the water was thermostated in the storage tank 2 to 20 ± 0·5°C by the heater 7. The storage tank was automatically replenished from the municipal pipe by means of a float and a solenoid valve. The inlet and outlet water temperature was measured by mercury thermometers 6 to within ±0·1°C.

The inert (air) was supplied by ventilator 17 *via* heat exchanger 15, the humidification column 18, measuring branch with an orifice 5 and a mixer at the column bottom 14. The mixer was fed with ammonia from a pressure cylinder 8. Past the mixer and at the column exit the temperature of the gas was measured and the gas was sampled for analysis.

The packing proper consisted of six sheets of expanded metal with the mesh size 16 × 6 mm (length of the diagonals of the rhombs). The spacing of the sheets was 11·75 mm.

Working procedure. For a given velocity of gas and ammonia concentration we have gradually changed the density of irrigation.

The velocity of gas ranged between 0·5—3·0 m/s and the density of irrigation between 0·025 to 0·4 kg/ms.

Three to four samples of liquid and two samples of gas were drawn for each steady state experiment. The analysis of the liquid phase was carried out by acidimetric titration. The titrating agent was sulphuric acid; the titration indicator the bromphenol blue. The analysis of the gas phase was carried out in a similar way. The sample of gas was passed through two bubbling washers in series containing diluted sulphuric acid of known concentration and an indicator while the volume of gas was measured, required to alter the blue colour of the solution. The second, check bubling washer caught only a negligible amount of ammonia.

Independent measurement of the interfacial area was carried out by the chemical method based on absorption of carbon dioxide in a water solution of sodium hydroxide. The concentration of CO_2 in air was 2—3% by volume. The continuously drawn sample at the inlet and outlet of the packing were dried by silica gel in U-tubes and fed into a 1 m long kyvette of the Zeiss interferometer. The comparing kyvette contained dry air free of CO_2. The correct function of the interferometer was verified by standard gas mixtures of known content of CO_2 in air. The concentration of sodium hydroxide and sodium carbonate in the liquid phase was determined by acidimetric titration.

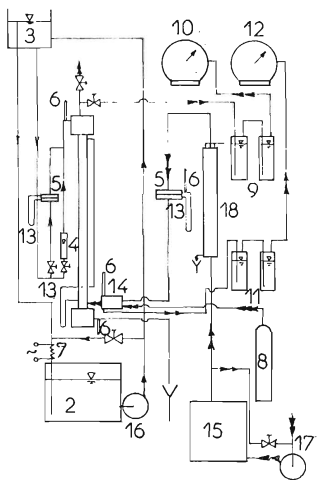

FIG. 1

Scheme of Experimental Set-Up

1 Absorption column, 2 water tank, 3 overflow tank, 4 rotameter, 5 orifice, 6 thermometers, 7 heater, 8 pressure cyclinder, 9 bubbling washers, 10 laboratory gasometer, 11 bubbling washer, 12 laboratory gasometer, 13 U-manometer, 14 mixer, 15 air cooler, 16 pump, 17 ventilator, 18 humidification column.

Data processing. After the basic processing of experimental data, following immediately the analyses of the exit streams, the mass transfer coefficient in the gas phase was computed from

$$k_g a = (G_{in}/FL) \int_{Y_p}^{Y_k} \{[1 + Y(M/\varrho)_{s1}][1 + Y^*(M/\varrho)_{s1}]/(Y - Y^*)\}\, dY, \qquad (6)$$

where

$$Y^* = (p^*/P)(\varrho/M)_{s1}/[1 - p^*/P], \qquad (7)$$

$$p^* = \exp[2{\cdot}303(-1\,750/T + 1{\cdot}1 \log c + 7)] \qquad (8)$$

and

$$c = (G_{in}/G_w)(Y - Y_p). \qquad (9)$$

A linear course of temperature throughout the column was assumed in the form

$$T = T_p + Y(T_p - T_k)/(Y_p - Y_k) \qquad (10)$$

in order to calculate -p^*-. The integral in Eq. (*6*) was found numerically after substituting for -Y^*-.

The following values were used in Eq. (*5*):
$\nu = 1{\cdot}55 \,.\, 10^{-5}$ m^2/s; $D = 1{\cdot}98 \,.\, 10^{-5}$ m^2/s; $(\nu/D) = 0{\cdot}783$; $F(\nu/D) = 1{\cdot}261$; $\phi(\nu/D) = 2{\cdot}37$; $d_e = 4F/0 = 2d_d = 23{\cdot}5 \,.\, 10^{-3}$ m and $L = 2{\cdot}0$ m.

The determination of the interfacial area is based on the evaluation for the rate of absorption accompanied by chemical reaction of the pseudo-first order[2]

$$Ra = ac_r \sqrt{(D_A k_2 c_B)} = k_g a(Y' - Y'_r). \qquad (11)$$

The rate of absorption Ra in Eq. (*11*), after expressing concentration of carbon dioxide in the liquid at the interface by

$$c_r = HY'_r \qquad (12)$$

is substituted after rearrangement into the expression for the mass balance on carbon dioxide in an infinitesimal volume of height dL

$$u_b\, dY' = Ra\, dL. \qquad (13)$$

Integration of E. (*13*) yields for the specific interfacial area the expression

$$a = Hu_b \ln(Y'_p/Y'_k)/\{L\sqrt{(D_A k_2 c_B)}[1 - u_b \ln(Y'_p/Y'_k)/(Lk_g a)]\}. \qquad (14)$$

Eq. (*14*) accounts for the correction on the effect of the gas side resistance. The diffusivity, solubility of carbon dioxide in the solution and the reaction rate constant were obtained from well-known relationships[2].

RESULTS

Table I summarizes the results of the specific interfacial area determined by the chemical method, which, expectedly increases with the density of irrigation. However, these results for the given density of irrigation practically do not depend on the

TABLE I

Specific Interfacial Area of Liquid Obtained by the Chemical Method

u_b	$\Gamma = 0{\cdot}026$	0·041	0·058	0·078	0·131	0·187	0·249
0·485	72·6	89·6	—	145·8	168·3	196·3	230·4
1·04	75·3	77·0	114·5	139·4	168·8	202·5	207·7
2·04	78·4	77·2	108·7	142·4	167·7	180·4	217·1
2·95	70·7	91·1	121·2	164·7	207·1	231·6	226·7
Average	74·3	83·7	114·8	148·1	178·0	202·7	220·5

TABLE II

Specific Interfacial Area of Liquid Obtained Computationally from $k_g a$ Values and the Theoretical Expression for k_g

u_b	$\Gamma = 0{\cdot}027$	0·038	0·054	0·081	0·138	0·220	0·384
0·83	61·97	80·66	129·14	150·58	173·95	—	—
1·11	60·73	85·71	103·63	168·89	215·15	274·40	—
2·07	68·49	76·41	94·43	128·07	164·19	208·71	269·48
2·90	53·46	79·20	—	127·27	177·03	183·25	216·78
Average	61·16	80·50	109·00	143·70	182·58	222·12	243·13

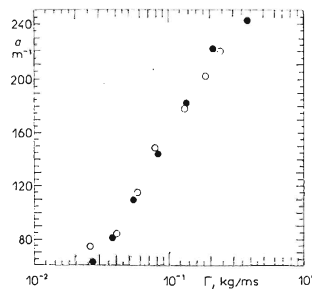

FIG. 2

Interfacial Area of Liquid *versus* Density of Irrigation

○Values obtained by the chemical method, ● values computed from $k_g a$ using the theoretical expression for k_g.

velocity of gas. In the evaluation of the experimental data on the gas side volume mass transfer coefficient $(k_g a)_{exp}$, we assumed validity of Eq. (5) for $k = k_g$ dimensionless hydrodynamic parameters identical to those for the single phase flow in a tube $\delta_l^+ = 1$ and $\lambda_p^+ = 20$ and calculated the specific interfacial area from

$$a = (k_g a)_{exp}/k_g \,. \qquad (15)$$

The obtained values are summarized in Tables II and depend also primarily on the density of irrigation while remain practically independent of the velocity of gas. Fig. 2 plots mean values of the specific interfacial area determined by the chemical method (Table I) and computed assuming validity of the theoretical relationship (5) (Table II) in dependence on the density of irrigation. From Fig. 2 it is apparent that the values of the interfacial area obtained by the two different methods well agree, which corraborates validity of Eq. (1) for mass transfer coefficients on the given packing also under the conditions of two-phase counter-current flow when the magnitude of the interfacial areas has been markedly changed.

LIST OF SYMBOLS

a	specific interfacial area (m^{-1})
c	concentration in the bulk liquid (kmol m^{-3})
d_d	spacing of the sheets (m)
d_e	equivalent diameter (m)
D	diffusivity ($m^2\ s^{-1}$)
e	porosity
F	column cross sectional area (m^2)
$F(\nu/D)$	function defined in the previous paper[1]
f	friction coefficient
G	flow rate ($m^3\ s^{-1}$)
H	coefficient defined in Eq. (12)
k	mass transfer coefficient (ms^{-1})
k_g	gas side mass transfer coefficient (ms^{-1})
k_2	reaction rate constant (m^3 kmol^{-1} s^{-1})
L	effective length of packing sheets (m)
M	molecular density (kg kmol^{-1})
O	wetted perimeter (m)
p	pressure (Pa)
Δp	pressure drop (Pa)
P	total pressure (Pa)
Ra	rate of absorption per unit volume (kmol m^{-3} s^{-1})
T	temperature (K)
u_b	superficial velocity (ms^{-1})
u^*	friction velocity (ms^{-1})
Y	gas concentration per unity volume of inert (kmol m_{in}^{-3})
Y'	gas concentration (kmol m^{-3})

δ_l thickness of laminar layer (m)
δ_l^+ dimensionless thickness of laminar boundary layer
λ_p thickness of transition layer (m)
λ_p^+ dimensionless thicknes of transition layer
λ_t length scale of turbulenece in region of fully developed turbulenece (m)
ε rate of energy dissipation in unit mass (Wkg^{-1})
$\phi(\nu/D)$ function defined in the previous paper[1]
ϱ density ($kg\ m^{-3}$)
ν kinematic viscosity ($m^2\ s^{-1}$)
Γ density of irrigation ($kg\ m^{-1}\ s^{-1}$)

Subscripts

A carbone dioxide
B hydroxyl ions
in inert
k finite value
p initial value
r interface
sl component
w water
* equilibrium value

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