THE GAS SIDE MASS TRANSFER COEFFICIENT IN THE TURBULENT FLOW IN A PACKING WITH A SIGNIFICANT DEPENDENCE OF THE INTERFACIAL AREA ON THE DENSITY OF IRRIGATION

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Received February 7th, 1083

A theoretically derived relationship has been applied for the gas-side mass transfer coefficient to experimental values of k_G. The experimental data have been obtained under the two-phase flow of gas and liquid in a plane vertical packing manufactured of the expanded metal sheet. This packing exhibits a significant dependence of the extent of interfacial area, and hence the geometry of the channel available for gas flow, on the density of irrigation.

In the earlier presented model of mass and heat transfer from an interfacial surface into an turbulent phase[1] we had assumed the existence of three hydrodynamic regions. These were the laminar boundary layer, the transition layer and the region of the developed turbulenece. These layers were characterized by their length scales δ_1, λ_p and λ_t; in the case of the transition and the turbulent region time scales were also used. In the cited paper the model was applied to heat and mass transfer under the single phase flow through a tube of circular cross section with smooth walls. In the relationship for the coefficient of mass transfer, modified to a form with the dimensionless lengths scales of the laminar and the transition regions δ_1^+ and λ_p^+, these hydrodynamic quantities were taken to be free parameters. From a pair of values of the Schmidt number, differing by as much as two orders of magnitude, and from the corresponding values of the mass transfer coefficients the following value $\delta_1^+ = 1$ and $\lambda_p^+ = 20$ were obtained. We noted the good agreement of these values with the thickness of the laminar and the transition layer following from the hydrodynamic measurements. In addition we also noted the good agreement of the experimental values of the mass and the heat transfer coefficients measured by various authors with the values computed from the model with the use of $\delta_1^+ = 1$ and $\lambda_p^+ = 20$. This good agreement was found in a wide range of both the Reynolds and the Schmidt or the Prandtl numbers (over more than five orders of magnitude).

The boundaries between individual hydrodynamic regions, considered in the model, are in reality neither immobile nor exactly distinguishable. The thickness of the laminar and the transition region must be therefore taken to be means averaged over the length and time intervals substantially greater than those given by the appropriate length and time scales characterizing the flow in individual layers. This, of course, applies also to analogous quantities obtained in the hydrodynamic studies.

In the cited paper it was shown that in the case of a straight channel there always exists a layer of liquid adhering to the wall where the turbulent disturbances do not penetrate either at all or only exceptionally. In case of a rough wall, or in places where the vector of the mean fluid velocity is not parallel to the wall of the channel, such a layer need not exist. It may be therefore expected that the hydrodynamic quantities δ_1^+ and λ_p^+ depend on the geometry of the channel, *i.e.* on its shape and roughness. For channels with a rougher surface or for channels, whose walls are not parallel to the flow of the bulke liquid, the mean values of the thickness of the laminar and the transition layer may be expected to be smaller than for straight tubes with smooth walls.

This work has been devoted to the application of the earlier model[1] to the data on the coefficient of mass transfer under the two-phase flow of liquid and gas through a plane vertical packing made of expanded metal sheet. The liquid flows over the parallel sheets of the expanded metal and the gas flows through the channel between individual sheets. The structure of the expanded metal sheets is spatial. On the spatially protruding diagonals of the expanded metal sheet structure there are practically no surfaces parallel to the plane of these sheets. The spacing of the sheets is usually made four to ten times the "thickness" of the expanded metal sheet, the latter being about 1·6 to 2·5 mm. The ribs (diagonals) of the expanded metal sheets have sharp edges. In region of low densities of irrigation (Γ less than 0·03 to 0·05 kg/ms) the liquid flows only over the ribs of the expanded metal sheets while rounding off their edges. In the region of high densities of irrigation (Γ greater than 0·14 to 0·25 kg/m s) the film of liquid fills the mesh of the expanded metal sheets. The walls of the channel are then formed by a continuous film of liquid but a substantial part of it is not parallel to the vector of mean gas velocity. In the region of intermediate liquid rates part of the mesh of the expanded metal sheets is empty and part is covered by the liquid film. With increasing rate of irrigation the fraction of the mesh covered by liquid increases. The geometry of the channel thus strongly depends on the flow rate of liquid.

The aim of this work has been to find out how the variable geometry of the walls of the channel affects the parameters of the model – the thickness of the laminar and the transition layer. For the application of the model we have chosen as most suitable the results[2] of measurement of $k_G a$ for absorption of SO_2 into a water solution of NaOH, supplemented by the results of measurement of the interfacial surface by the method of CO_2 absorption into a solution of NaOH. The concentrations of the solution of NaOH were the same for both types of measurements and the experiments were carried out in the same apparatus. It may be therefore assumed that k_G obtained from these experiments truly represents the gas-side mass transfer.

THEORETICAL

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

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

The functions $F(v/D)$ and $\phi(v/D)$ following from the solution of the partial differential equations representing the statement of the model, are given as sums of infinite series and their combination. Their exact values may be computed from the tabulated values of the functions[3]. For practical calculations one can use the following approximations with an error less than 1%

$$\begin{aligned} &\text{for} \quad v/D \leqq 1 && F(vD) = 1 + (v/D)/3 \\ &\text{for} \quad v/D \geqq 3 && F(v/D) = (2/\pi^{1/2})\,(v/D)^{1/2} \\ &\text{for} \quad 1 < v/D < 3 && F(v/D) = 1{\cdot}32(v/D)^{0.358} \end{aligned} \qquad (2)$$

and

$$\begin{aligned} &\text{for} \quad v/D \leqq 1 && \phi(v/D) = 2/(v/D) - 1/3 \\ &\text{for} \quad v/D \geqq 11 && \phi(v/D) = 0 \\ &\text{for} \quad 1 < v/D < 11 && \phi(v/D) = 1{\cdot}755(v/D)^{-1.278} - 0{\cdot}075\,. \end{aligned}$$

In the case of the two-phase flow of liquid and gas through a channel, the expressions for the friction velocity and the energy dissipated in a unit mass of gas are given by

$$u^* = (1/2)\,[(\Delta p_G d_e)/(h\varrho_G)]^{1/2} \qquad (4)$$

and

$$\varepsilon = (\Delta p_G u_r)/(h\varrho_G e)\,. \qquad (5)$$

The quantities Δp_G stand for the pressure loss corresponding to the energy dissipated solely in the gas phase. Part of the total energy lost by gas on passing through the channel is transferred to the film of liquid and this part is being dissipated in the liquid phase. For Δp_G we have proposed in the preceding paper[2] the following expression

$$\Delta p_G = \Delta p \mp a_0(z - z_0)\, g h/2 \qquad (6)$$

The upper sign $(-)$ in Eq. (6) holds for the counter-current flow, the lower for the occurrent flow. The relationships for the relative velocity of gas with respect to the film of liquid, u_r. the void fraction, e, the characteristic length scale, d_e, the hold-up of liquid, z, z_0, are also presented in the previous paper[2].

From Eq. (*1*) we obtain, after substituting Eqs (*4*) and (*5*), for the gas-side mass transfer coefficient under the two-phase flow

$$k_G = [F(\nu/D)/(\nu/D)]\,[(\Delta p_G d_e)/(h\varrho_G)]^{1/2}/\{2[\delta_1^+ F(\nu/D) + \lambda_p^+] + \\ + [(\Delta p_G d_e^2 e)/(h\varrho_G u_r \nu)]^{1/4}\,\phi(\nu/D)\}\,. \qquad (7)$$

For the calculation of the parameters of the model, δ_1^+ and λ_p^+ one can modify Eq. (*7*) to the form

$$\delta_1^+ F(\nu/D) + \lambda_p^+ = 0{\cdot}5\{[F(\nu/D)/(\nu/D)]\,[(\Delta p_G d_e)/(h\varrho_G)]^{1/2}/k_G - \\ + [(\Delta p_G d_e^2 e)/(h\varrho_G u_r \nu)]^{1/4}\,\phi(\nu/D)\}\,. \qquad (8)$$

The separation of the values δ_1^+ and λ_p^+ in the expression on the left hand side of Eq. (*8*) is possible only on the basis of measurements at sufficiently different values of the Schmidt number.

EXPERIMENTAL

The experiments in the previous work[2] were carried out in a column of rectangular cross section 103 × 70·5 mm with 0·95 m long packed section. In order to eliminate the effect of the entrance and the exit section of the column additional experiments were carried out with an effective length 0·35 m. The resulting values of the mass transfer coefficient and pressure drop correspond to the difference of the appropriate extensive quantities (the number of transfer units, interfacial surface and pressure drop across the column) for the shorter and the longer section.

During the measurements of $k_G a$ by absorption of SO_2 into a solution of NaOH the inlet concentration of SO_2 amounted to 0·015 to 0·05% by volume. During measurements of the interfacial surface by absorption of CO_2 into NaOH solutions under the conditions of the pseudo-first order reaction the inlet concentration of CO_2 amounted to 1·5 to 2% by volume. The initial concentration of NaOH in both measurements was 0·5 kmol/m^3.

The measurements were carried out both in the counter-current and co-current flow arrangement. The range of liquid flow rates was $\Gamma = 0{\cdot}0165$ to 0·307 kg/ms. The experimental superficial gas velocities covered the range from 0·7 to 3·5 m/s in case of the counter-current flow and up to 3·8 m/s for the cocurrent flow. A more detailed description of the apparatus, the method of measurement and the basic data processing were given in the previous paper[2].

For the evaluating of the expression $\delta_1^+ F(\nu/D) + \lambda_p^+$ the following values were used $\nu/D = 1{\cdot}10$; $F(\nu/D) = 1{\cdot}37$ and $\phi(\nu/D) = 1{\cdot}48$.

RESULTS AND DISCUSSION

Experimental values of k_G from the previous work were processed by using Eq. (*8*). The parameter $\delta_1^+ F(\nu/D) + \lambda_p^+$ in the measured range was found independent of gas velocity (Reynolds number) and the flow arrangement (counter-current and cocurrent flow arrangement). This may be apparent from Fig. 1. An exception to this are results of measurement at Γ = 0·208 kg/m s, where the average value of the parameter is by 13% lower for the cocurrent flow than for the counter-current flow arrangement. This, however, is a random error. Appart from that, for the counter-current flow arrangement at high flow rates of liquid (near the flooding) a decrease appears of the parameter by about 15 to 30%. A possible cause may be the action of the stream of gas on the film of liquid inducing a change of the geometry of the channel (separation of the film of liquid from the surface of the packing) even at constant rate of liquid.

Fig. 2 shows the dependence of the parameter $\delta_1^+ F(v/D) + \lambda_p^+$ (averaged for constant rate of the density of irrigation) on the density of irrigation. In region of Γ below 0·1 kg/m s the dependence of the parameter on the density of irrigation appears significant. With decreasing density of irrigation the value of the parameter also decreases. Physically this finding may be interpreted as follows: Decreasing density

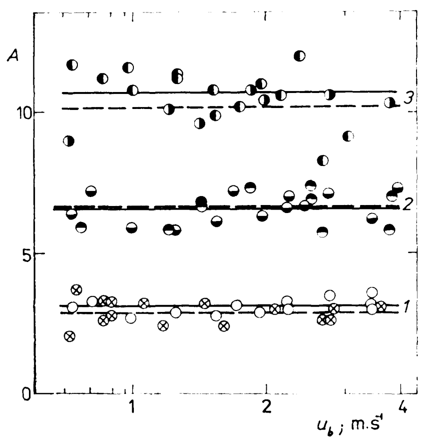

FIG. 1

Plot of experimental values of $\delta_1^+ F(v/D) + \lambda_p^+$ *versus* gas velocity $A = \delta_1^+ F(v/D) + \lambda_p^+$; ——— average value of A counter-current flow; ----- average value of A for cocurrent flow; *1* 0·0165 kg/ms, ○ counter-current, ⊗ cocurrent flow; 2 0·0425 kg/ms, ⊖ countercurrent, ⊖ cocurrent flow; *3* 0·260 kg/ms, ◐ counter-current, ◑ cocurrent flow

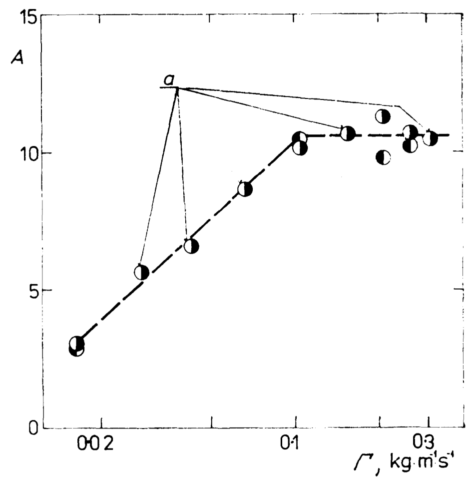

FIG. 2

Plot of $\delta_1^+ F(v/D) + \lambda_p^+$ *versus* density of irrigation. A arithmetic mean of experimental values of $\delta_1^+ F(v/D) + \lambda_p^+$ at constant density of irrigation; ◑ counter-current, ◐ cocurrent flow, *a* values of A for counter-current and cocurrent flow graphically undistinguishable of irrigation increases the "roughness" of the walls of the channel which in turn diminishes the average thickness of the laminar and the transition layers. For Γ above 0·1 kg/m s no dependence of the parameter on the density of irrigation in the measured interval was detected. This may be explained by the fact that the geometry of the channel, after all its mesh has been filled by liquid, alters little with the change of the density of irrigation. This change practically does not influence the thickness of the laminar and the transition layer.

In the range of the Schmidt numbers, plausible for the two-phase gas–liquid flow it is impossible to distinguish in the parameter $\delta_1^+ F(\nu/D) + \lambda_p^+$ the thickness of the laminar and the transition layers. This fact, seen as a disadvantage from the standpoint of the theoretical analysis, appears as an advantage from the practical standpoint. The expression (7) for the calculation of the gas side mass transfer coefficient, characterizing the transfer into the turbulently gas phase (for absorption, rectification, evaporation), thus contains a single parameter dependent solely on the geometry of the channel where the transfer takes place.

LIST OF SYMBOLS

a	specific interfacial surface area, m^{-1}
a_0	specific surface of the packing (twice the area of the expanded metal sheet related to a unit volume of the packing)
d_e	equivalent diameter, m
D	diffusivity, $m^2 s^{-1}$
e	void fraction
$F(\nu/D)$	function of the Schmidt number defined in the previous paper[1]
g	acceleration due to gravity, ms^{-2}
h	height of packed section, m
k_G	gas side mass transfer coefficient, $m s^{-1}$
Δp	overall pressure drop, Pa
Δp_G	pressure loss by friction of gas, Pa
u_b	superficial velocity of gas, $m s^{-1}$
u_r	relative gas velocity within the packing with respect to flowing film, $m s^{-1}$
u^*	friction velocity, $m s^{-1}$
z	hold-up of liquid related 1 m^2 of expanded metal sheet, $kg m^{-2}$
z_0	liquid hold-up at $\Delta p = 0$
Γ	rate of irrigation of liquid per unit length of irrigated edge of the sheets, $kg m^{-1} . s^{-1}$
δ_1	thickness of the laminar boundary layer, m
δ_1^+	dimensionless thickness of the laminar boundary layer
ε	rate of energy dissipation in unit of mass, $W kg^{-1}$
λ_p	length scale of turbulence in the transition layer, m
λ_p^+	dimensionless thickness of the transition layer
λ_t	length scale of turbulence in region of fully developed turbulence, m
ν	kinematic viscosity, $m^2 s^{-1}$
ϱ_G	gas density, $kg m^{-3}$
$\phi(\nu/D)$	function of the Schmidt number defined in the previous paper[1]

REFERENCES

1. Kolář V.: This Journal *42*, 1310 (1977).
2. Červenka J., Brož Z., Kolář V.: This Journal, in press.
3. Crank J.: *The Mathematics of Diffusion*, p. 47. Oxford University Press, Oxford 1956.

Translated by V. Staněk.