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Experimental studies of momentum transfer in a gas–liquid system in the vicinity of an agitated vessel wall

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The results of an experimental investigation of transport processes at the wall of an agitated vessel in a gas–liquid system are presented. Measurements were carried out by means of the electrochemical method. The experiments were performed in a standard agitated vessel of diameter 0.3 m, equipped with a Rushton disc turbine and baffles. The distributions of the diffusion current along the vessel wall were obtained for different values of agitator speed and superficial gas velocity. On the basis of these data, distributions of the shear rate, shear stress, dynamic velocity, friction coefficient and energy dissipated were evaluated. The mean values of the $\overline{\gamma/n}$ and $\bar{f}$ variables were approximated analytically.

List of symbols

A_1, A_2	exponents in Equations 7 and 11
a	length of agitator blade (m)
B	width of baffle (m)
b	width of agitator blade (m)
C_1, C_2	coefficients in Equations 7 and 11
D	inner diameter of agitated vessel (m)
d	agitator diameter (m)
e	distance between dispersing ring and bottom of the vessel (m)
f	friction coefficient
g	gravitational acceleration ($m\,s^{-2}$)
H	height of the liquid in the vessel (m)
h	distance between disc of the agitator and bottom of the vessel (m)
I_d	diffusion current (A)
n	agitator speed (s^{-1})
v^*	dynamic velocity ($m\,s^{-1}$)
$\dot{V}_g$	gas flow rate ($m^3\,s^{-1}$)
w_{og}	superficial gas velocity, $w_{og} = \dot{V}_g/(\pi D^2/4)$ ($m\,s^{-1}$)
Z	number of agitator blades
z	axial coordinate (m)
α	heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
γ	shear rate (s^{-1})
ϕ	angular coordinate (deg)
η	dynamic viscosity (Pa s)
ρ	liquid density ($kg\,m^{-3}$)
τ	shear stress ($N\,m^{-2}$)
ϵ_m	energy dissipated ($W\,kg^{-1}$)

Dimensionless numbers

$Nu = \alpha D/\lambda$	Nusselt number
$Re = nd^2\rho/\eta$	Reynolds number
$Fr = w_{og}^2/gD$	modified Froude number

1. Introduction

Mechanical agitation of gas–liquid systems is frequently applied for intensification of chemical and biochemical processes. Because transport phenomena in the boundary layer of the agitated vessel occur at various points of the wall with different intensity, knowledge of the distribution of the parameters which describe momentum transfer for a gas–liquid system in the vicinity of the vessel wall is important for design purposes.

For example, on the basis of such information, it is possible to calculate local values of the heat transfer coefficient, α, from the theoretical equation [2]

$$\frac{\alpha D}{\lambda} \sim Pr^{1/3}\ \frac{v^* D}{\nu} \qquad (1)$$

in which v^* denotes local dynamic velocity at the wall of the agitated vessel.

Transport processes can be investigated using the electrochemical method [4, 7–10] and theory for new types of electrode has recently been developed [11, 12]. The electrochemical method can also be applied in studies of transport processes occurring at the walls of agitated vessels. Mass [1, 6], heat [3] and momentum transfer [13–16] in this region have been successfully measured by means of this technique. However, results of investigations of momentum transfer have been obtained for the liquid phase only.

The purpose of the present work was to study momentum transfer at an agitated vessel wall in a gas–liquid system.

2. Theory

Quantitative relationships exist between the limiting diffusion current, I_d, and coefficients describing momentum transfer. The shear rate, γ, at the wall of

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an agitated vessel can be evaluated from the equation [16]

$$\gamma = kI_d^3 \tag{2}$$

where k is a constant depending on the physical properties and concentration of the electrolyte and on the surface area of the measuring electrode.

The shear stress, τ, and dynamic velocity, v^*, at the wall of the agitated vessel can be calculated for Newtonian fluids as follows

$$\tau = \eta\gamma \tag{3}$$

$$v^* = \sqrt{(\tau/\rho)} \tag{4}$$

where η and ρ denote dynamic viscosity and density of the liquid, respectively.

The friction coefficient, f, at the wall of the agitated vessel is defined by the following equation [14, 15]:

$$f = \frac{\tau D^2}{\rho n^2 d^4} \tag{5}$$

The energy, ϵ_m, dissipated at the wall of the agitated vessel can be evaluated from the following equation:

$$\epsilon_m = \frac{\tau\gamma}{\rho} \tag{6}$$

The parameters, γ, τ, v^*, f and ϵ_m, are local values, depending on the position at the wall of the agitated vessel.

3. Experimental details

Measurements of the distribution of the diffusion current along the height of the agitated vessel wall were carried out for the regions of two-phase flow, defined in [5] as states (b) and (c), i.e. for conditions of gas dispersion in the liquid without and with recirculation of gas in the agitated vessel. The experiments were conducted for superficial gas velocity, w_{og}, varied between $2 \times 10^{-3}\,\mathrm{m\,s^{-1}}$ and $5.1 \times 10^{-3}\,\mathrm{m\,s^{-1}}$ and agitator speeds, n, varied between $4.2\,\mathrm{s^{-1}}$ and $7.5\,\mathrm{s^{-1}}$.

The electrochemical system used involved the reduction of potassium ferricyanide to potassium ferrocyanide. The electrolyte had a composition of 0.01 M potassium ferricyanide, 0.05 M potassium ferrocyanide, and 0.5 M sodium hydroxide. The liquid temperature was maintained 20 °C.

The experimental setup is shown in Fig. 1. The agitated vessel (1) of inner diameter $D = 0.3$ m, filled by electrolyte up to height $H = D$, was made from Plexiglass and consisted of two segments of height $h_1 = 0.3$ m. The agitated vessel was equipped with four, symmetrically placed, baffles (2) of width $B = 0.1D$ and a Rushton disc turbine (5) of diameter $d = 0.33D$ (number of blades $Z = 6$; length of blade $a = 0.25d$, width of blade $b = 0.2d$ and distance between disc of the agitator and bottom of the vessel $h = d$). In the lower segment of the agitated vessel, 32 circular nickel cathodes (3) of diameter $d_c = 4$ mm were built flush with the vessel wall. A nickel sheet 10 cm × 10 cm, lying on the bottom of the agitated vessel, was used as the anode (4). Air was dispersed in the agitated vessel by means of a ring (18) of diameter $d_d = 0.7d$, placed under the agitator at the distance $e = 0.5h$ from the bottom of the vessel.

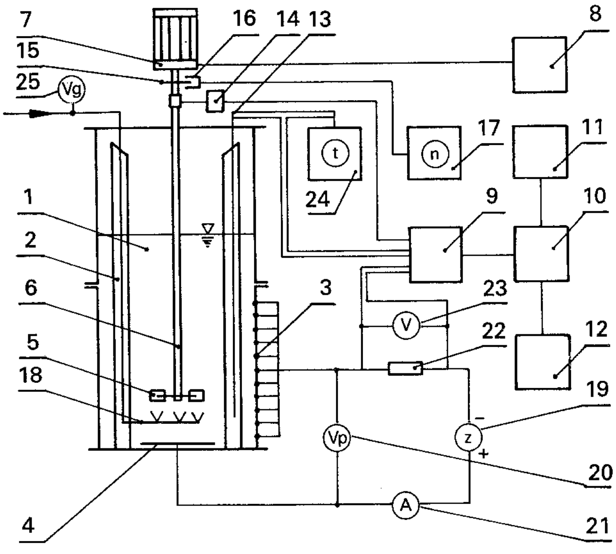

Fig. 1. Experimental setup. (1) Agitated vessel, (2) baffle, (3) cathode, (4) anode, (5) Rushton disc turbine, (6) shaft, (7) electric motor, (8) steering unit, (9) card AD/DA, (10) microcomputer IBM AT, (11) monitor, (12) printer (13) measuring probe, (14) tachometer, (15) perforated disc, (16) photoelectric sensor, (17) digital display, (18) gas distributor, (19) potential source, (20), (23) digital voltmeter, (21) ammeter, (22) resistor, (24) thermostat, (25) rotameter.

The temperature of liquid was recorded using measuring probes (13), consisting of 50 copper–constantan thermocouples. The agitator (5) was driven by an electric motor (7). The agitator speeds were directly measured by means of a photoelectric method using a sensor (16).

The electric circuit for measurement of the diffusion current contained the cathodes (3), the anode (4), a potential source (19), digital voltmeters (20) and (23), an ammeter (21) and a precise resistor (22).

The temperature of the liquid, the agitator speeds and the diffusion current were also processed by means of a microcomputer IBM AT (10) equipped with an analog/digital convertor (9), 12-bit card ADDA. The card (9) made it possible to convert voltage from analog to digital and to sample actual voltage values from the measuring probe (13), tachometer (14) and voltmeter (23). From the mean values of the voltage, output quantities were calculated and displayed on the monitor (11). Results of the measurement were recorded by printer (12).

Positions of the measuring electrodes at the agitated vessel wall are shown in Fig. 2. The cathodes were placed in four vertical rows which are denoted by numbers I, II, III and IV. The rows have different location in relation to baffles. Therefore it was possible to carry out experiments in two positions: before and behind the baffle.

4. Results and discussion

In total, 512 experimental values of the intensity of diffusion current, I_d, as a function of the axial and angular coordinates (z, ϕ), agitator speed, n, and superficial gas velocity, w_{og}, were obtained. On the basis of these data, 16 distributions of the diffusion

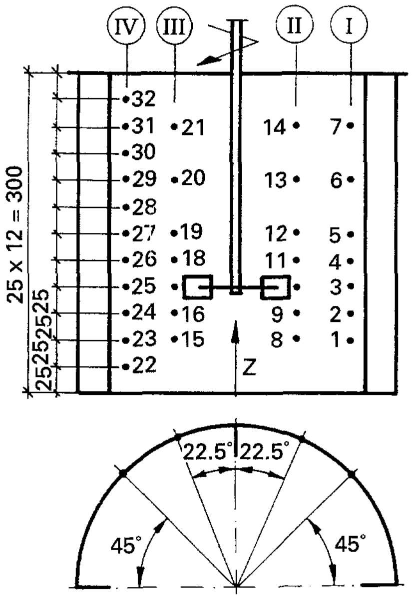

Fig. 2. Positions of measuring cathodes.

current along the height of the agitated vessel wall can be plotted.

For example, the experimentally obtained course of the function $I_d = f(z/H)$ at coordinate $\phi = 45°$ is shown in Fig. 3. This illustrates distribution of the diffusion current intensity along the agitated vessel wall for different agitator speeds at a superficial gas velocity, $w_{og} = 3.93 \times 10^{-3}\,\mathrm{m\,s^{-1}}$. The current increases as the agitator speed increases, with the exception of the data obtained for $n = 7.5\,\mathrm{s^{-1}}$ and range of the geometrical parameter $z/H > 0.75$. Surface aeration of liquid, which starts at this agitator speed, is thought to be responsible for this anomaly.

In comparison with the axial coordinate, the influence of angular coordinate on the value of the diffusion current is significantly smaller.

On the basis of the experimental values of I_d, the

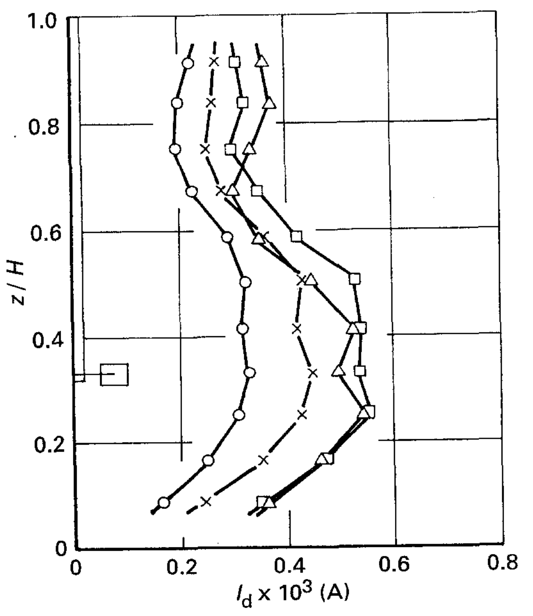

Fig. 3. Distribution of diffusion current I_d along the wall of the agitated vessel. Key for n: (○) 4.2, (×) 5.0, (△) 6.7 and (□) $7.5\,\mathrm{s^{-1}}$. $w_{og} = 3.93 \times 10^{-3}\,\mathrm{m\,s^{-1}}$.

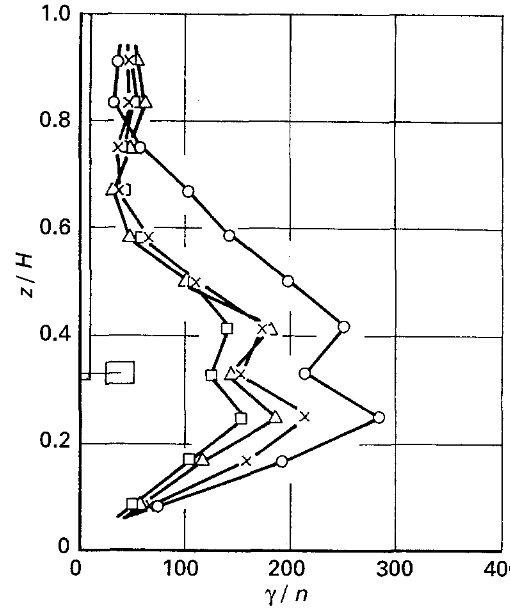

Fig. 4. Distribution of dimensionless shear rate γ/n along the wall of the agitated vessel. Key for $w_{og} \times 10^3$: (○) 1.97, (×) 3.14, (△) 3.93 and (□) $5.11\,\mathrm{m\,s^{-1}}$. $n = 6.7\,\mathrm{s^{-1}}$.

quantities γ, γ/n, τ, v^*, f and ϵ_m were calculated, according to definitions (Equations 2–6).

The distribution of the shear rate along the height of the agitated vessel wall is presented in Fig. 4, in the form of the dimensionless function $\gamma/n = f(z/H)$, for different superficial gas velocities and an agitator speed, $n = 6.7\,\mathrm{s^{-1}}$. Analysis of the curves in Fig. 4 shows that, within the range of the geometrical parameter z/H between 0 and 0.75, the function γ/n decreases if the value of the velocity w_{og} increases. The variability of this function is not important in the range of z/H between 0.75 and 1. Furthermore, a local minimum is clearly revealed in the region of the agitator, exactly at the point which corresponds to the position of the turbine disc. This is associated with the so-called stagnation point, which arises at the point of perpendicular impact of the fluid stream on the wall.

Mean values of the dimensionless shear rate $\overline{\gamma/n}$ for the whole height of the agitated vessel wall were calculated from local values $\gamma/n = f(z/H), \phi)$ using numerical integration.

A set of the averaged data $\overline{\gamma/n} = f(Re, Fr_g)$ has been correlated in the form

$$\overline{\gamma/n} = C_1 Re^{A_1} \tag{7}$$

where

$$Re = \frac{nd^2\rho}{\eta} \tag{8a}$$

$$A_1, C_1 = f(Fr_g) \tag{8b}$$

$$Fr_g = \frac{w_{og}^2}{gD} \tag{8c}$$

Detailed expressions for exponent A_1 and coefficient C_1 in Equation 7 are as follows:

$$A_1 = 0.75(1 - 6.86 \times 10^4 Fr_g) \tag{9}$$

$$C_1 = 4.22 \times 10^{-2}(1 + c_1 Fr_g + c_2 Fr_g^2 + c_3 Fr_g^7) \tag{10}$$

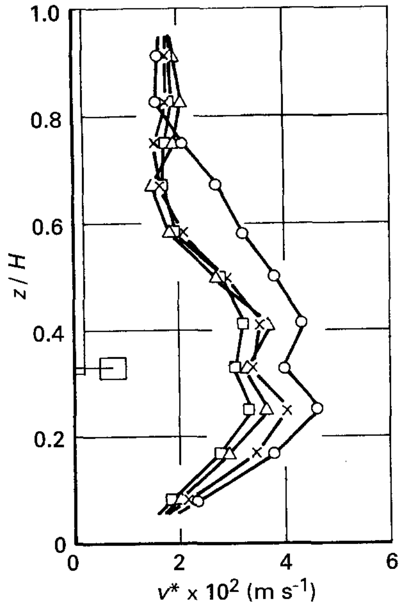

Fig. 5. Distribution of dynamic velocity v^* along the wall of the agitated vessel. Key for $w_{og} \times 10^3$: (○) 1.97, (×) 3.14, (△) 3.93 and (□) 5.11 m s^{-1}. $n = 6.7$ s^{-1}.

where $c_1 = -5.28 \times 10^5$, $c_2 = 2.46 \times 10^{11}$ and $c_3 = 5.36 \times 10^{36}$. For example: $A_1 = 0.75$ and $C_1 = 4.22 \times 10^{-2}$ for $w_{og} = 0$; $A_1 = 0.48$ and $C_1 = 0.24$ for $w_{og} = 3.93 \times 10^{-3}$ m s^{-1}.

Equation 7 is formulated for liquid ($w_{og} = 0$), as well as, for the gas–liquid system and approximates the results of the measurements with mean relative error ±5%, within the range of dimensionless numbers as follows: Re between 3×10^4 and 7×10^4 and Fr_g between 2×10^{-6} and 9×10^{-6} for gas–liquid system, and Re between 1.5×10^4 and 6×10^4 for liquid.

Typical distributions of the dynamic velocity, v^*, at the wall of the agitated vessel are presented in Fig. 5. To date information about numerical values of this quantity has not been published in the literature for mechanically agitated gas–liquid system. Knowledge

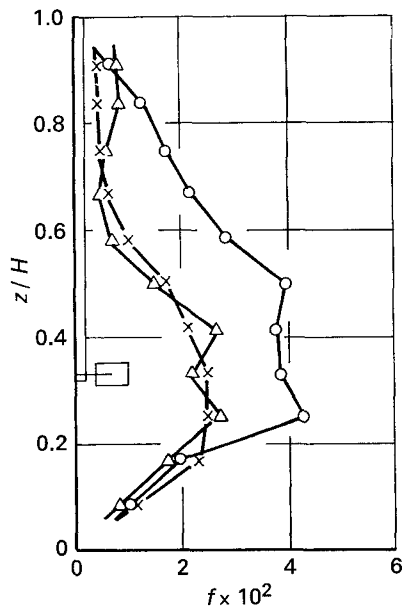

Fig. 6. Dependence $f = F(z/H)$ for $n = 6.7$ s^{-1}. Key for $w_{og} \times 10^3$: (○) 0, (×) 1.97 and (△) 3.9 m s^{-1}. $n = 6.7$ s^{-1}.

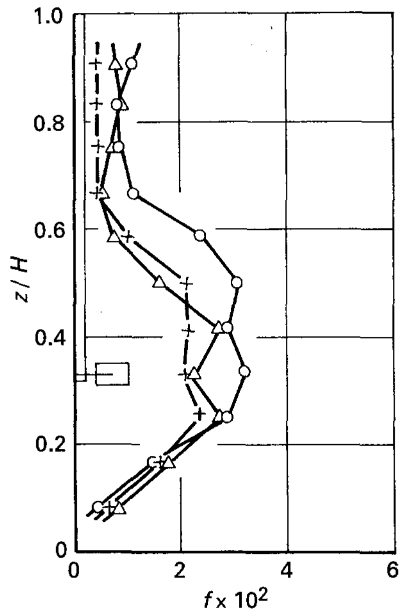

Fig. 7. Dependence $f = F(z/H)$ for $w_{og} = 3.93 \times 10^{-3}$ m s^{-1}. Key for n: (○) 4.2, (△) 6.7 and (+) 7.5 s^{-1}. $w_{og} = 3.9 \times 10^{-3}$ m s^{-1}.

of the distributions of v^* or τ is important because these quantities are present in the theoretical equation for calculation of the local value of the heat transfer coefficient at the wall of jacketed agitated vessels.

Distributions of the friction coefficient, f, at the wall of the agitated vessel are shown in Figs 6 and 7. For comparison, the data for liquid (without gas) are also plotted in Fig. 6. It can be seen that the loading of the gas into liquid results in a decrease of the friction coefficient, f. Fig. 7 illustrates the distribution of the coefficient f, for constant values of the superficial gas velocity and different values of the agitator speed. In general, the friction coefficient, f, decreases as the agitator speed increases. Furthermore, some deformation of the distribution curve is observed with increase in n.

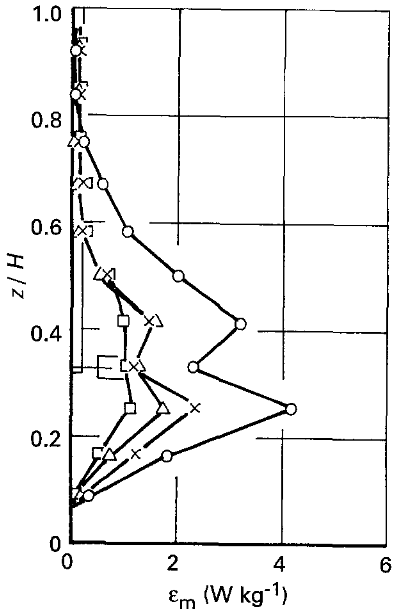

Fig. 8. Distribution of energy dissipated ϵ_m along the wall of the agitated vessel. Key for $w_{og} \times 10^3$: (○) 1.97, (×) 3.14, (△) 3.93 and (□) 5.11 m s^{-1}. $n = 6.7$ s^{-1}.

Mean values of the friction coefficient, $\bar{f}$, were calculated from local values by numerical integration. The set of data $\bar{f} = F(Re, Fr_g)$ was approximated analytically by

$$\bar{f} = C_2 Re^{A_2} \quad (11)$$

where

$$A_2 = -0.25(1 + 2.12 \times 10^5 Fr_g) \quad (12)$$

$$C_2 = 0.38 \times 10^{(c_4 Fr_g + c_5 Fr_g^2)} \quad (13)$$

and where $c_4 = 1.68 \times 10^5$ and $c_5 = 6.29 \times 10^9$. For example: $A_2 = -0.25$ and $C_2 = 0.38$ for $w_{og} = 0$; $A_2 = -0.54$ and $C_2 = 4.30$ for $w_{og} = 3.93 \times 10^{-3}\,\mathrm{m\,s^{-1}}$.

Equation 11 approximates results of the measurements with mean relative error ±6%, within the range of Re between 1.5×10^4 and 6×10^4 for liquid phase ($Fr_g = 0$), and Re between 3×10^4 and 7×10^4, and Fr_g number between 1.3×10^{-6} and 9×10^{-6} for the gas–liquid system.

Distributions of the dissipated energy, ϵ_m, along the height of the agitated vessel wall are presented in Fig. 8, in the form of the function $\epsilon_m = f(z/H)$, for constant value of the agitator speed, n, and different superficial gas velocities, w_{og}. The greatest values of ϵ_m correspond to the least velocity $w_{og} = 1.97 \times 10^{-3}\,\mathrm{m\,s^{-1}}$. In the range of w_{og} between $3.14 \times 10^{-3}\,\mathrm{m\,s^{-1}}$ and $5 \times 10^{-3}\,\mathrm{m\,s^{-1}}$, the functions $\epsilon_m = f(z/H)$ decrease for values of the geometrical parameter z/H between 0 and 0.5 and they do not change within z/H between 0.5 and 1.

5. Conclusions

(i) Experimental studies have shown that momentum transfer at the wall of the agitated vessel is most intensive in the region of the agitator.

(ii) Values of the coefficients describing momentum transfer decrease as the gas flow rate in the agitated vessel increases.

(iii) On the basis of local values of the parameters characteristic of momentum transfer at the wall of the agitated vessel, the theoretical equation used for the calculation of heat transfer coefficient can be verified.

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