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Short communication

Dissolution of solid body in a tubular reactor with reciprocating plate agitator

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Abstract

Reciprocating plate agitator with flapping blades intensifies the mass transfer from motionless vertical solid cylinder to its no flowing surrounding dilute solution of rock salt. A unique correlating relation represents the results. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Mass transfer; Liquid–solid contacting operation; Reciprocating plate agitator

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1. Introduction

Studies on the effect of vibration on mass transfer to liquid have been relatively few. The majority of the mass transfer analysis was concentrated on the sublimation of vibrated solid body [1–4] or particles [5] to air, dissolution of solid body [6–8] or particles [6,9–12] in liquid or evaporation of small droplets of liquids [13] in an air stream. Typically, the insert samples used in most previous studies are spheres or cylinders. The authors of the works [14–20] have investigated the mass transfer characteristics of a disc column. The above works have been devoted to the study of mass transfer of a multistage vibrating disc column for a case of liquid–liquid extraction operation [14,16–18] and for case of gas–liquid absorption [15,19,20]. The dissolution of solid particles into water and several other solutions has examined by Tojo et al. [11], where agitation was realized by using circular flat disc with no perforation. The mass transfer coefficients are calculated by measuring the slope of the concentration time curve in the first second of particle dissolution. Condoret et al. [10] studied mass transfer around an active sphere located in bed of inert spheres with oscillating flow of liquid. The electrode is polarized within the bed and surface electrochemical reaction is controlled be mass transfer. The flat part of potential curve allows direct measurement of the mass transfer coefficient. The oxygen mass transfer in a reciprocating plate reactor for an air–water system was studied by Gagnon et al. [20] and an overall mass transfer coefficient calculated from the dissolving oxygen response curves.

From the data available in the technical literature it is clear that the attention has not been focused upon the contacting operation for a case of dissolution solid body into a liquid mixed by reciprocating plate agitator with flapping blades. It is realized in the following section.

2. Experimental

The intensification of the dissolution under the action of reciprocating plate agitator was carried out using the reactor shown in Fig. 1. It consisted of the vertical vessel, the system for measuring mass of dissolving solid body (rock-salt), the device for measuring concentration in the bulk of mixed liquid (water) and the arrangement for reciprocating of a plate agitator at various amplitudes and frequencies. The agitation was carried out with a single reciprocating plate with flapping blades oriented horizontally where it reciprocated in a vertical direction. Schematic diagram of the agitator is shown in Fig. 2 . Description of the agitator is given in the complete patent specifications [21]. Main dimensions of the mixing vessel and the agitator are given in Table 1. Two conductivity probes did the measurements of concentration of the achieved dilute solution of the salt. One of them was mounted near the bottom, the other one at the upper part of the mixer. The concentration changing in time was recorded using a multifunction computer meter (CX-732, Elmetron, Gliwice, Poland). Typical example of the concentration time

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Nomenclature

a	width of windows in the plate (m)
A	amplitude (m)
b	clearance between plate and exhaust edge of flapping blade (m)
c	concentration (kg NaCl/kg)
d	diameter of agitator (m)
d_h	$d_h = (4F_{cl} + F_{clw})/(P_{cl} + P_{clw})$, hydraulic diameter (m)
d_s	diameter of sample (m)
D	inner diameter of vessel (m)
f	frequency (s^{-1})
F_{cl}	$F_{cl} = \pi/4(D^2 - d^2)$, area of clearance ($m^2$)
F_{clw}	$F_{clw} = 4ab$, area of windows in the plate (m^2)
k	mass transfer coefficient (m/s)
l_s	length of sample (m)
m	mass (kg)
P_{cl}	$P_{cl} = \pi(D - d)$, wetted perimeter of clearance (m)
P_{clw}	$P_{clw} = 8(a + b)$, wetted perimeter of windows (m)
Re	$Re = 2\pi Afd_h\rho/\mu$, Reynolds number
Sc	$Sc = \mu/D\rho$, Schmidt number
Sh	$Sh = \bar{d}_s\bar{k}/D$, mean Sherwood number

Greek letters

μ	viscosity (Pa s)
ρ	density (kg/m^3)
τ	time (s)

response curve for two electric conduction probes is given in Fig. 3. The mass of the NaCl sample decreasing during the process of dissolution we have determined by an electronic balance (WPE 300, RAWAG, Radom, Poland) that connected with rocking double-arm lever. On the lever arm the sample was hanging, the other arm was connected to the balance. The lever was mounted on a bracket through a system bearing. The mounting had been done in way that a precise placing of a hanging salt sample in the mixer was possible. The lever had been mounted on precise micro bearings, thanks to which the change of mass loss of the solid body being the results of dissolving was measured without any losses.

3. Results and discussion

3.1. Sample

The method used to experimentally investigate mass transfer from solid body to its no flowing surrounding dilute solution was the dissolution of rock salt in water. This method was chosen because the salt is relatively inexpensive and may be readily turned on the lathe into cylinder. Furthermore, the dissolution process may be followed simple by measuring the loss in weight of the sample between the beginning and the end of run. Raw rock-salt (>98% NaCl and rest traces quantitative of chloride of K, Ca, Mg and insoluble mineral impurities) cylinders were not fit directly for the experiments because their structure was not homogeneous (certain porosity). Basic requirement concerning the experiments was creating possibly homogeneous transport conditions of mass on whole interfacial area, which was the area of the solid body. These requirements were met thanks to proper preparing of the sample, mounting it in the mixer and matching proper time of dissolving. As an evident effect were fast showing big pinholes on the surface of the dissolved sample as results of local non-homogeneous of material. Departure from the shape of a simple geometrical body made it impossible to take measurements of its area with sufficient precision. So it was necessary to put those samples through the process of so-called hardening. The turned cylinders had been soaked in saturated brine solution for about 15 min and than dried in a room temperature. This process was repeated four times. To help mount the sample in the mixer, a thin copper thread was glued into the sample's axis. The processing was finished with additional smoothing of the surface with fine-grained abrasive paper. A sample prepared in this way had been keeping its shape during dissolving for about 30 min. The duration of a run was usually 2 min. The rate of mass transfer involved did not produce significant dimensional change in diameter of the cylinder. The time of a single dissolving cycle was chosen so that the measurement of mass loss could be made with sufficient accuracy and the decrease of dimensions would be relatively small (maximum about 0.5 mm).

Before starting every experiment, a sample which height, diameter and mass had been known was mounted in a mixer under the free surface of the mixed liquid. The reciprocating plate agitator was started, the recording of concentration changes in time, the weight showing changes in sample's mass during the process of solution, and time measuring was started simultaneously. After finishing the cycle of dissolving, the agitator was stopped, and then the loss of mass Δm had been read on electronic scale and concentration of NaCl (electric conductance) in the mixer as well. The salt sample was taken out from the mixer. To show that the measurements of the area were done properly, the measurement of the volume was done in the measuring cylinder filled with saturated solution of NaCl. Maximum difference between volumes of the samples calculated and measured was less then ±4%. The sample was dried and measured. If there were no pinholes on the sample and its shape did not differ much from the shape of cylinder, dried sample was again put into mixer and next measurement took place.

3.2. Mass transfer coefficient

The mass transfer coefficient in a mixing process was calculated from a mass balance between a dissolving cylinder

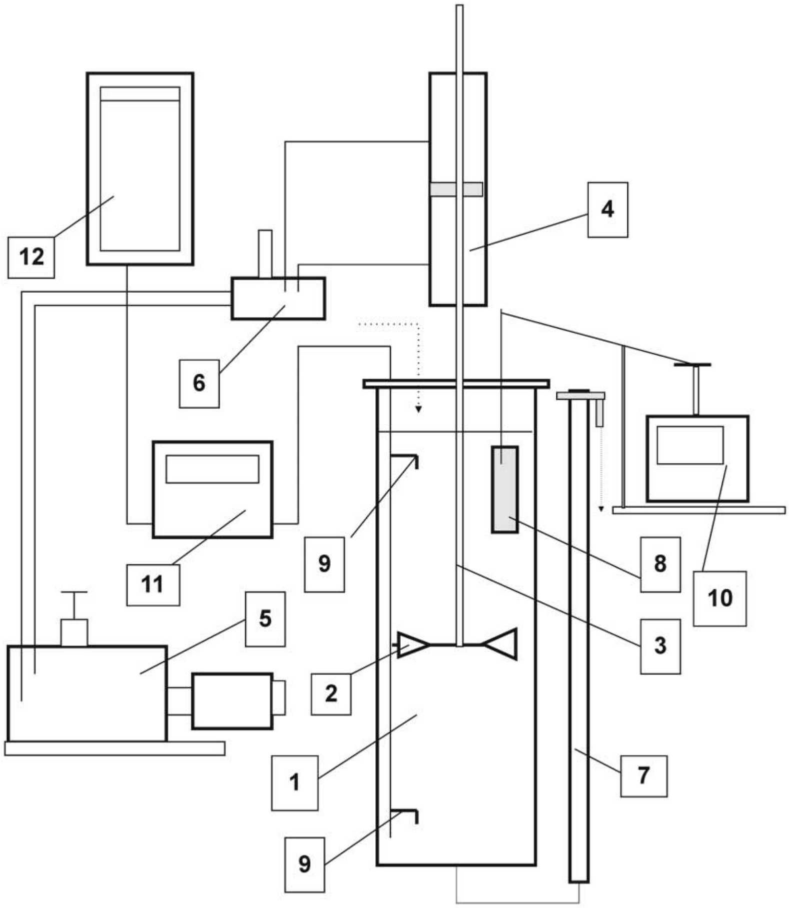

Fig. 1. Experimental set-up: (1) vessel; (2) agitator; (3) shaft; (4) hydraulic cylinder; (5) variable-delivery pump; (6) control valve; (7) overflow; (8) sample; (9) probe; (10) electronic balance; (11) conductivity bridge, (12) recorder.

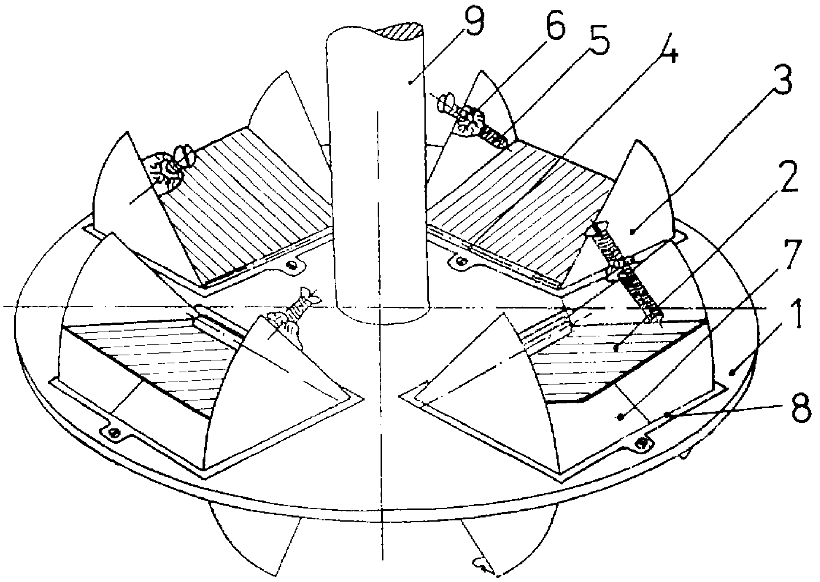

Fig. 2. Schematic diagram of the agitator: (1) plate; (2) blade; (3) shield; (4) sleeve; (5) limiter; (6) weld nut; (7) free windows for liquid flow; (8) housing; (9) shaft.

Table 1
Dimensions of mixer and operating conditions

Mixer and sample parameters	Operating range
Inner diameter of vessel (m)	0.205
Vessel length (m)	1.033
Height of liquid level in the vessel (m)	0.995
Plate diameter (m)	0.204
Width of windows in the plate (m)	0.039
Plate length (m)	0.036
Clearance between the plate and exhaust of the blade (m)	0.015–0.024
Hydraulic diameter (m)	0.00386–0.01
Mean diameter of sample (m)	0.011–0.0316
Mean length of the sample (m)	0.03–0.065
Amplitude (m)	0.03–0.19
Frequency (s^{-1})	0.087–1.429
Time of dissolution (min)	2
Loss of mass for 2 min dissolution (kg)	$(0.14–6.83) \times 10^{-3}$
Mean driving force (kg NaCl/kg sol)	0.002–0.0137

and its surrounding solution that it may be written in the following differential form:

$$\mathrm{d}m_{\mathrm{NaCl}}(\tau) = k_{\mathrm{NaCl}}(c,\tau)F_{\mathrm{s}}(\tau)\,\mathrm{d}c_{\mathrm{NaCl}}(\tau)\,\mathrm{d}\tau \tag{1}$$

Eq. (1) cannot be integrated because the area of solid body, F_{s}, is changing in time of dissolving process. It should be noted that in the present investigation the change in mass of solid body in a short time period of dissolving is very small and the mean area of dissolved cylinder may be used. The driving force of the process $\mathrm{d}c_{\mathrm{NaCl}}(\iota)$ was calculated from two time response curves as the arithmetic mean $\Delta\bar{C}_{\mathrm{NaCl}}$ and it is used in Eq. (1) instead actual value of driving force.

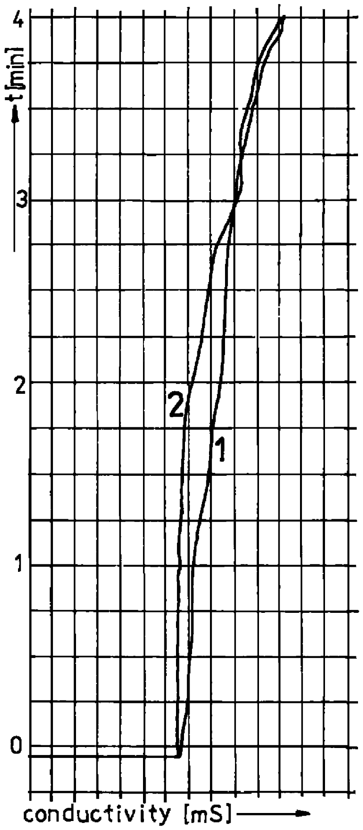

Fig. 3. Typical example of conductivity curve: (1) near the free surface of liquid; (2) above bottom of tubular vessel.

Based on the accurate experimental data the relation between loss of mass, mean area of mass transfer and mean driving force for 2 min of dissolving duration is approximately linear and then the mass transfer coefficient may be defined generally by the following equation:

$$\bar{k}_{\mathrm{NaCl}} = \frac{\Delta m_{\mathrm{NaCl}}}{\bar{F}_{\mathrm{s}}\,\Delta\bar{C}_{\mathrm{NaCl}}\,\Delta\tau} \tag{2}$$

Using the above equation an average values of coefficient $\bar{k}_{\mathrm{NaCl}}$ were calculated for all experimental data obtained in the present work. This technique is widely used in practical design of the mass transfer in mixing vessel with rotary agitators.

3.3. Mass transfer characteristics

Under convective conditions a relationships for the mass transfer similar to the relationships obtained for heat transfer may be expressed, of the form [22]

$$Sh = f(Re, Sc) \tag{3}$$

The mean Sherwood number is based on the diffusion coefficient of rock salt in water and mean diameter of cylinder. The Reynolds number is defined using the peak velocity of the plate and hydraulic diameter. The dimensions groups are calculated with the physical properties at the mean bulk liquid temperature. In order to establish the effect of the Reynolds number on mass transfer coefficient data obtained in this work are graphically illustrated in a $\log Sh/Sc^{1/3}$ versus $\log Re$ system in Fig. 4. From this figure follows that the own experimental data preserve the trend accepted by various researchers for mean turbulent convection with data scatter at typical level. The exponent upon of the Schmidt number is to be 1/3 [3,7,8,10–12] as there is some theoretical and experimental evidence for this value [3], although reported values vary from 0.56 [4] to 1.13 [1]. Jameson [8] has used this value in the first in an investigation of mass transfer from a cylinder oscillating with simple harmonic motion in studies an infinite body of fluids. Fig. 4 demonstrates that, within the limits of scatter among the plotted data represented by the points, the mean Sherwood number increase with increase in the Reynolds number. The relation between the experimental results shown in Fig. 4 can be described this relationship, which when written in dimensionless groups used herein has the form

$$Sh = 0.17(Re\,Sc)^{1/3} + 0.11Re^{0.5}\,Sc^{1/3} \tag{4}$$

The final correlation, Eq. (4), was obtained for the studied configuration and it is valid for following range of process parameters: $Re = 130–5400$, $Sc = 874–1244$.

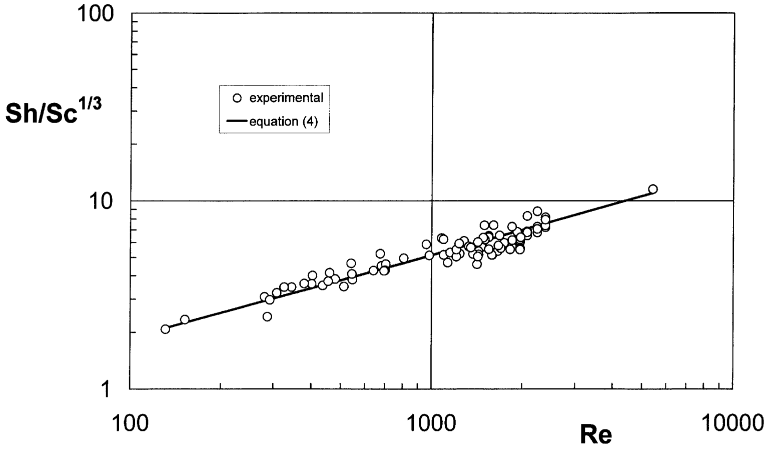

Fig. 4. Effect of the Reynolds number on the mass transfer rate.

Fig. 4 presents a graphical form of Eq. (4), as the full curve, correlated the data very well with standard deviation $\sigma = 0.66$. The average percentage error of all the data is -1.3%. The difference between the predicted and measured values of the Sherwood number is less than ±15% for approximately 80% of the data points. The agreement is satisfactory for engineering design purpose.

4. Concluding remarks

The main concluding remarks concerning the mass transfer in a reactor equipped with reciprocating plate agitator which results from the present investigation may be briefly summarized as follows:

1. Eq. (4) is the same form as it has been proposed in Refs. [7,11–13] for mass transfer from solid single sphere or spherical particles into controlled stream of fluid.
2. In the present work, where mass transfer experiments have been carried out using cylindrical samples, the value of the Sherwood number in the limit as Péclet → 0 would be difficult to calculate from two points of view. First and foremost it is uncertainly in the periodic velocity field formed near the dissolving cylindrical sample that is located near the wall of the tubular vessel. Moreover, the lower part of the sample was located at the great distance (0.2 m) above the flapping blades. Secondly, from technical viewpoint it is difficult to carry out of the measurements of the concentration at the boundary layer owing to great size of electric conductivity probe.
3. From comparison of the result of own investigations with the experimental findings reported in Refs. [3,7,8,10], it can be seem that the rate of mass transfer reported by the those authors are greater than one obtained in this work. When dissolution of a solid body is required, process is complicated. The concentration boundary layer around the sample decreases forced convective mass transfer. Reduction of the thickness layer is greater at high deformation of velocity field. This can be done, however, only in the continuous phase, since there is no possibility carried over the mixing directly inside the layer. When we decided to place the agitator near the sample the streams beat the sample and then the temporary fluctuation mass of dissolving body is recorded as a stochastic signal. It is insignificant when the sample vibrated and then the mass transfer rate is measured by recording the time response of concentration inside the reactor. In this paper mass decrement of the sample and the accretion of concentration in the bulk of the mixed liquid are recorded.
4. Explanation of the basic transport phenomenon in the reciprocating plate reactor (RPR) leads to an understanding vibratory mixing principles. It is very important in the dynamic behavior of the continuous RPR (CRPR) and the analysis of residence time distributions. To apply this basic understanding in more detail another technical report has been provided.
5. With respect to the other very useful mass transfer equations given in the pertinent literature the equation predicted in the present paper is much more attractive because it generalizes the experimental data without the break through the all regimes of flow in a relatively simple and uniform manner.

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