ABSORPTION OF OXYGEN INTO ELLIS LIQUID

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The authors studied absorption of oxygen by aqueous solutions of poly(acrylamide) which showed a pseudoplastic behaviour. The results were described by equations involving dimensionless criteria modified for the Ellis flow model. The equations were compared with those published for the power flow model.

A review of works[1-10] dealing with mass transfer in absorption of gases by non-Newtonian liquids reveals a partial disagreement of the published data due both to different rheological properties of the studied liquids and different experimental techniques. The rheological properties of non-Newtonian liquids are most often described by the two-parameter power model (Ostwald–de Waele model), because it is simple; however, it is not theoretically founded.

In our preceding work[11] the results obtained in studying absorption of oxygen by aqueous solutions of poly(acrylamide) were described by criterion equations in which the dimensionless criteria were modified for the case where the flow curve was described by a power model. It follows from the parameters of this model that the aqueous solutions of poly(acrylamide) under study[11] exerted a pseudoplastic behaviour, however especially at low polymer concentrations their pseudoplasticity was not marked. Therefore, the three-parameter Ellis model was used to describe the flow curves more accurately. The present work gives correlation criterion equations for transfer of oxygen into poly(acrylamide) solutions whose rheological behaviour is described by the three-parameter Ellis flow model.

THEORETICAL

For the case of absorption of a slightly soluble gas into a non-Newtonian liquid in an apparatus with a wetted sphere, the dependence of the intensity of mass transfer on hydrodynamic conditions and mass properties of the liquid phase can be expressed[11] by the criterion equation

$$\mathrm{Sh} = b_1\, \mathrm{Re}_{\mathrm{m}}^{a_1} \mathrm{Sc}_{\mathrm{m}}^{a_2}\,, \qquad (1)$$

where the Reynolds and Schmidt numbers were modified for the power flow model.

If the relation between the shear rate and the shear stress is described by the Ellis flow model in the form

$$\dot{\gamma} = \Phi_0 \tau + \Phi_1 \tau^\alpha , \qquad (2)$$

it is possible to find by qualitative analysis that the intensity of mass transfer during absorption, characterized by the liquid side mass transfer coefficient, k_L, depends on the gas diffusivity in the liquid, D, on the velocity of the liquid, u, its density, ϱ, and on the parameters of the flow model, Φ_0, Φ_1. These involve also the characteristic dimension of the bed particles, d (equal to their diameter if they are spherical). Since the dimensions of these seven quantities can be formed as products of powers of three basic dimensions (mass, length and time), it is possible to derive four independent dimensionless criteria. Besides the Sherwood number,

$$\mathrm{Sh} = k_L d / D , \qquad (3)$$

we have derived the criterion

$$\pi_1 = d u \varrho \Phi_0 , \qquad (4)$$

which characterizes the hydrodynamic conditions and can be expressed for the flow of liquid over the surface of spherical particles in the form

$$\pi_1 = 4 \dot{V} \varrho \Phi_0 / \pi d , \qquad (4a)$$

further

$$\pi_2 = d^{2\alpha - 2} \Phi_0^\alpha / D^{\alpha - 1} \Phi_1 , \qquad (5)$$

which characterizes the diffusivity of gas absorbed in an Ellis liquid, and

$$\pi_3 = d^{2\alpha - 2} \Phi_0^{2\alpha - 1} \varrho^{\alpha - 1} / \Phi_1 , \qquad (6)$$

which involves the characteristic dimension of the bed particles, the density of the liquid, and the parameters of the Ellis flow model.

EXPERIMENTAL

Experiments were carried out in a model absorber with a wetted spherical particle. The experimental set-up was described earlier[11]. The wetting liquid was either tap water or aqueous solutions of two sorts of poly(acrylamide) (VEB Fettchemie, Karl-Marx-Stadt G.D.R.), namely Neuperm WF ($\langle M \rangle_n = 13\,600$ g mol^{-1}, $\langle M \rangle_m = 14\,100$ g mol^{-1}) and Stipix ($\langle M \rangle_n = 114$ g mol^{-1}, $\langle M_m \rangle = 259\,000$ g mol^{-1}). The mass averages of the molecular weights of the polymers were determined by the viscosimetric method, and the numerical averages by osmometry. The rate of flow of oxygen was maintained at 3 000 cm^3 min^{-1} (20°C, 98 kPa), and the rate of liquid flow was varied between 50 and 260 cm^3 min^{-1}. The temperature of measurement was 20°C.

The dependences of the shear stress on the shear rate for the tested poly(acrylamide) solutions were measured on a rotating viscosimeter Rheotest II in the experimental range of the shear rates. The parameters Φ_0, Φ_1, and α of the Ellis flow model were evaluated from the rheograms; they are given in Table I together with other physical properties of the poly(acrylamide) solutions.

The diffusivity of oxygen was measured on the same experimental set-up in the same solutions by the method described earlier[12]. The apparatus was calibrated by measuring the diffusivity of oxygen in tap water at 20°C; the result was $1{\cdot}96 \,.\, 10^{-9}$ m^2 s^{-1} in accord with the published data[13].

RESULTS AND DISCUSSION

The dependences of the coefficient of oxygen transfer at the liquid side on the rate of flow of the poly(acrylamide) solutions are given and discussed in ref.[11]. In short, the transfer coefficient increases with the rate of flow, the increase becoming less pronounced when the polymer concentration increases. At a given rate of flow the coefficient of oxygen transfer decreases with increasing concentration of the polymer.

From these data and other quantities considered, we calculated the dimensionless criteria as indicated by Eqs (*3*)–(*6*); further we calculated by the multiple linear regression method the values of regression coefficients in the criterion equation

$$\mathrm{Sh} = b_2\, \pi_1^{a_3} \pi_2^{a_4} \pi_3^{a_5} \qquad (7)$$

TABLE I

Physical properties of aqueous solutions of poly(acrylamide) at 20°C

c wt. %	ϱ $kg\,m^{-3}$	Φ_0 $kg^{-1}\,m\,s$	Φ_1 $kg^{-\alpha}\,m^{\alpha}\,s^{2\alpha-1}$	α	$D\,.\,10^9$ $m^2\,s^{-1}$
		Neuperm WF			
1·0	1 000·2	359·8	12·08	1·70	4·16
2·5	1 002·4	170·4	6·08	1·90	4·37
5·0	1 006·1	56·1	2·00	1·92	5·51
		Stipix			
0·25	999·5	367·2	11·75	2·10	5·71
0·50	1 001·0	145·5	7·00	2·14	5·40
0·75	1 002·2	113·0	3·26	2·26	4·02

assumed to hold good for both sorts of poly(acrylamide). The calculations were done on an EC 1033 computer. Thus, for aqueous solutions of Neuperm we obtained the equation

$$\mathrm{Sh} = 1\,090\, \pi_1^{0.329} \pi_2^{-0.026} \pi_3^{-0.011} \qquad (8)$$

(correlation coefficient 0·976), and for aqueous solutions of Stipix

$$\mathrm{Sh} = 0{\cdot}796\, \pi_1^{0.332} \pi_2^{0.229} \pi_3^{0.018} \qquad (9)$$

(correlation coefficient 0·955). The values of the dimensionless criteria π_1, π_2, and π_3 varied in wide ranges 0·705 – 23·4, $4{\cdot}84 \cdot 10^8 - 1{\cdot}35 \cdot 10^{10}$, and $2{\cdot}88 \cdot 10^5 - 1{\cdot}73 \cdot 10^6$, respectively, for the Neuperm solutions, and 1·41 – 23·8, $1{\cdot}06 \cdot 10^{11} - 1{\cdot}06 \cdot 10^{12}$, and $1{\cdot}69 \cdot 10^7 - 1{\cdot}21 \cdot 10^8$, respectively, for the Stipix solutions. However, since the influence of π_2 in Eq. (*8*) and π_3 in Eqs (*8*) and (*9*) on the value of Sh is not marked, we expressed the correlation equations in the approximate forms

$$\mathrm{Sh} = 561\, \pi_1^{0.297} \qquad (10)$$

for Neuperm solutions (correlation coefficient 0·973) and

$$\mathrm{Sh} = 1{\cdot}26\, \pi_1^{0.334} \pi_2^{0.224} \qquad (11)$$

for Stipix solutions (correlation coefficient 0·953). Hence, it is apparent that the transfer of oxygen is in the former case governed by the criterion π_1 and in the latter by the criteria π_1 and π_2.

Similar findings were described in our preceding work[11] using the criterion equation (*1*), where the Reynolds and Schmidt numbers were modified for the power flow model. For Stipix solutions, the influence of the modified criteria Re_m and Sc_m on the Sherwood number was marked, whereas for Neuperm solutions it was sufficient to consider only the correlation between Sh and Re_m. Equations (*10*) and (*11*) also show that the criterion π_1, characterizing the hydrodynamics, has a larger influence on Sh for the Stipix solutions than for Neuperm. A similar tendency was observed with Re_m in the correlation equations obtained in ref.[11]. The differences in absorption of oxygen into aqueous solutions of the two sorts of poly(acrylamide) are probably due to different distributions of macromolecules, as follows from the different mass and numerical averages of the molecular weights.

Criterion equations for absorption of CO_2 into water in a vertical disc column were evaluated in refs[14–16]. At low flow rates of the liquid, Re has an exponent ranging from 0·33 to 0·47 and Sc has one ranging from 0·25 to 0·50. According to Eqs (*10*) and (*11*) and the conclusions in ref.[11], however, the influence of the hydrodynamic criterions π_1 and Re_m (in Eq. (*1*), $a_1 = 0{\cdot}30$ for Stipix and 0·27 for Neuperm) as well as of the criterions π_2 and Sc_m (in Eq. (*1*), $a_2 = 0{\cdot}19$ for Stipix) is for the transfer of oxygen into poly(acrylamide) solutions smaller than the influence of Re and Sc reported by other authors[14-16]. The different conclusions may be due to the fact that during flow through the vertical disc column the liquid is stirred as it passes between the bed particles, and further that the film of the poly(acrylamide) solution is more stable than that of water, which forms a ripple surface influencing the mass transfer during absorption. Also, it should be mentioned that the changes of the values of π_2 and Sc_m were not due to a change in the temperature of the liquid, but only to changes in the polymer concentration. Although the values of the parameters of the Ellis model were not appreciably different for the solutions of both sorts of poly(acrylamide), the criterion equations modified either for the Ellis or for the power[11] model gave for the two polymer sorts different results: For Neuperm, whose mass and numerical averages of the molecular weight were comparable, the intensity of oxygen transfer was influenced only by hydrodynamic conditions, whereas for Stipix, whose mass and numerical averages of the molecular weight differed appreciably, the influence of mass properties was manifested besides. Thus, the transfer of oxygen into aqueous solutions of poly(acrylamide) is also influenced by the size of the polymer molecules.

Since the transfer of mass into non-Newtonian liquids presents many problems, it is necessary to verify the results of the present work on other non-Newtonian liquids.

LIST OF SYMBOLS

a, b	regression coefficients
c	concentration of polymer in solution, wt. %
D	diffusivity, $m^2\,s^{-1}$
d	diameter, m
k	consistency coefficient, $kg\,m^{-1}\,s^{n-2}$
k_L	liquid side mass transfer coefficient, $m\,s^{-1}$
$\langle M \rangle_m$	mass average of molecular weights, $g\,mol^{-1}$
$\langle M \rangle_n$	numerical average of molecular weights, $g\,mol^{-1}$
n	flow index
u	linear velocity of liquid, $m\,s^{-1}$
$\dot{V}$	volume rate of flow of liquid, $m^3\,s^{-1}$
α	parameter of Ellis flow model
$\dot{\gamma}$	shear rate, s^{-1}
μ	dynamic viscosity of liquid, $kg\,m^{-1}\,s^{-1}$
ϱ	density of liquid, $kg\,m^{-3}$
τ	shear stress, $kg\,m^{-1}\,s^{-2}$
Φ_0, Φ_1	parameters of Ellis flow model, $kg^{-1}\,m\,s$ and $kg^{-\alpha}\,m^{\alpha}\,s^{2\alpha-1}$
$Re = du\varrho/\mu$	Reynolds number
$Re_m = d^n u^{2-n} \varrho/k$	Reynolds number modified for the power model
$Sc = \mu/\varrho D$	Schmidt number

$\mathrm{Sc_m} = d^{2-2n}k/D^{2-n}\varrho$ Schmidt number modified for the power model
Sh Sherwood number
π_1, π_2, π_3 modified criteria for Ellis flow model

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