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Determination of the flow and heat transfer characteristics in non-Newtonian media agitated using the electrochemical technique

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Abstract

In the study the results of the friction factor in boundary layer and the distribution of heat transfer coefficient in non-Newtonian liquid agitated by different impellers, have been presented. It has been established that for studies in Na-CMC and guar gum aqueous solutions by the electrochemical method the following solution of 0.005 (kmol m^{-3}) $K_3[Fe(CN)_6]$, 0.005 (kmol m^{-3}) $K_4[Fe(CN)_6]$ and 0.3 (kmol m^{-3}) K_2SO_4 can be recommended. The common relationship (for a given type of an impeller) between local values of friction coefficient and heat transfer coefficient and Reynolds number proposed by Metzner and Otto [A.B. Metzner, R.E. Otto, Agitation of non-Newtonian fluids, AIChe J. 3 (1957) 3–10] for all power-law fluids, have been obtained.

Keywords: Agitation; Non-Newtonian fluids; Electrochemical method; Heat transfer coefficient distribution; Shear rate distribution; Friction factor distribution

1. Introduction

The electrochemical method is based on a diffusion-controlled reaction at the electrode surface and mass transfer between electrode surface and electrolyte solution. When an electric potential is applied between two electrodes in an aqueous solution of an electrolyte [1] an ionic reduction occurs at the cathode and an oxidation at the anode. As a result, a current which is proportional to the number of ions reacting at the electrodes per unit time, flows through the circuit. When the potential on the electrode is gradually increased the current first increases until a stable value is reached. This value is called the limiting current and it corresponds to the condition when the concentration of the reacting species of ions on the surface of the electrode equals zero. At steady state, ions that are converted at the electrode have to be supplied from the bulk of the liquid. This can occur by a diffusion process under the effect of the concentration gradient and by migration of the ions in the electric field. To suppress the last effect or make it negligible compared to diffusion and convection, a high concentration of inert electrolyte is used. In the electrochemical method during the transport of substance and charge in the electrolyte stream, ions from the main mass solution are transferred to the surface of the electrode. If the process is controlled only by the diffusion of the ions to the surface electrode, mass flux at the wall surface ($y = 0$) obeys the first Fick law. From the measurements of limiting current density the mass transfer coefficient k_m can be determined:

$$k_m = \frac{I_d}{C_\infty z_e F} \qquad (1)$$

The red-ox couple most often used in various studies is potassium ferricyanide–ferrocyanide. The indifferent electrolytes used were potassium sulphate and sodium hydroxide [2].

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Nomenclature

A_E	surface area (m^2)
B^*	the proportionality coefficient
c_F	friction factor
c_p	specific heat ($J\ kg^{-1}\ K^{-1}$)
$C_{p,p}$	mass concentration of polymer (%)
d	impeller diameter (m)
d_E	electrode diameter (m)
D	tank diameter (m)
D_A	diffusivity ($m^2\ s^{-1}$)
F	Faraday's constant ($C\ mol^{-1}$)
H	liquid height in a tank (m)
I_d	limiting diffusion current (A)
k_m	mass transfer coefficient ($m\ s^{-1}$)
K	consistency index ($Pa\ s^m$)
m	flow behaviour index
n	impeller rotational speed (s^{-1})
Pr_{MO}	Prandtl number for mixing power-law liquid
R_E	radius of cathode (m)
Re_{MO}	Reynolds number for mixing of power-law liquid
Sc_{MO}	Schmidt number for mixing of power-law liquid
T	temperature (K)
w	velocity ($m\ s^{-1}$)
z	axial coordinate
z_e	number of electrons taking part in a reaction
Greek symbols	
α	heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
η	viscosity (Pa s)
η_e	equivalent viscosity (Pa s)
ρ	density ($kg\ m^{-3}$)
τ	shear stress (Pa)
λ	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
$\dot{\gamma}_E$	shear rate (s^{-1})
$\dot{\gamma}_m$	average shear rate (s^{-1})
φ	angular coordinate

The electrochemical method has previously been applied in a variety of convective heat transfer and wall shear stress studies making use of well known analogies between the various transport phenomena. This measuring technique has been especially used for prior studies of the processes occurring in the boundary layer at the wall of the apparatus [2]. Also in chemical engineering this method has been used, for example: in the studies of pulsate and oscillate flows between parallel plate (plate heat exchanger) [3–6], in evaluation of the thickness of boundary layer in natural convection mass transfer [7–9], in the measurement of liquid film thickness in Newtonian [10] and non-Newtonian fluids [11], in pipes flow [12–15], in packed column [16,17], in fluidisation processes [18,19] and membrane reactor [20].

The aim of the present work was to determine experimentally the local distributions of shear rate, friction factor and heat transfer coefficient in non-Newtonian liquid agitated by different impellers. Previous literature [21–27] has not paid sufficient attention to introduce the electrochemical method to determination of the flow and heat transfer characteristics of the stirring when the non-Newtonian liquids are the media agitated.

2. Experimental set-up

Detailed construction of agitated vessel of diameter of $D = 0.19$ (m) used in the study is shown in Fig. 1a. Twelve nickel electrodes ($d_E = 5 \times 10^{-3}$ m) were placed at various heights along the tank wall. It should be pointed out that if the previous electrochemical experiments were carried out in an agitated solution, the electrode used had the diameters of $d_E \in (0.0002; 0.012)$ (m) [2,23,25–27]. Distance of the centre of electrodes from the tank bottom was taken as the value of z (axial coordinate). Application of twelve electrodes enabled the authors to carry out the measurements within the range of dimensionless coordinates $z/H \in (0.105, 0.974)$. In each study before the starting of measurements, the electrode surfaces were cleaned using the powdered aluminium oxide (Al_2O_3). Additionally, the nitrogen was used to remove the oxygen from the electrolyte solution.

On the tank bottom the opposite electrode (anode) made of the nickel plate about 0.10 (m) diameter, was mounted. The tank was provided with a heating-cooling jacket. The effect of an angular coordinate φ on the diffusion limiting current for non-Newtonian fluids has also been studied. The experimental studies were carried out for two model polymer solutions, carboxymethylcellulose sodium salt and guar gum, in the tank equipped with four various impellers: Rushton turbine, paddle with six pitched blade with angles of 45° and 135°, and the paddle with six blades with angle of 90°, for standard geometric invariants of the agitated vessel (Fig. 1b–e). The exemplary data of the limiting diffusion current is presented in Fig. 2. During the measurements for different solutions tested the exemplary limiting current values have been obtained as follows:

- for electrolyte solutions and Rushton turbine $I_d \in (1.7 \times 10^{-4}, 5.8 \times 10^{-4})$ (A),
- for Na-CMC aqueous solutions $I_d \in (1.2 \times 10^{-4}, 6.0 \times 10^{-4})$ (A),
- for guar gum aqueous solutions $I_d \in (1.1 \times 10^{-4}, 4.4 \times 10^{-4})$ (A).

3. Heat–mass transfer analogy

Chilton and Colburn [28] demonstrated that in turbulent tube flow the analogy between heat and mass transfer