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Experimental study of electrochemical mass transfer in an annular duct with the electrolyte nanofluid

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ABSTRACT

The paper shows experimental studies on mass transfer phenomena in the nanofluid flowing through an annular channel. The effect of aluminium oxide nanoparticles on mass transfer was investigated in the channel with hydraulic diameter 10.5 mm.

The experiment was performed using the electrochemical limiting current technique.

A classical system for mass transfer measurements, based on ferricyanide ion reduction at the cathode and ferrocyanide ion oxidation at the anode has been applied. The base fluid (base-electrolyte) was composed of equimolar potassium ferri-ferrocyanide solution and sodium hydroxide solution. The nanofluid tested (nano-electrolyte) was composed of the base-electrolyte and spherical, 99.9% pure aluminium oxide nanoparticles, of about 40 nm in diameter. The nano-electrolyte used was characterized by volume particle fractions: 0.005%, 0.01%, 0.015%, 0.02%, 0.025%, 0.04%, 0.05% and 0.06%.

Mass transfer processes during the forced transitional and turbulent flow of the nano-electrolyte through the horizontal annular channel were investigated. The fully developed hydrodynamic profile was considered. Mass transfer coefficients at the cathode attached to the inner surface of the channel were measured. The experiment was performed with the Reynolds numbers ranging from 2080 to 10430. Bulk ion concentrations in the electrolyte were measured experimentally during each test which minimized errors resulting from ion concentration decomposition. There occurred changes in the mass transfer coefficients depending both on nanoparticle concentration and the Reynolds number. With an increase in nanoparticle fraction, mass transfer was reduced. Measurements for the transitional and turbulent regime indicated that the mass transfer coefficients achieved their lowest values at the largest value of nanoparticle fraction. However, the reduction in mass transfer was not proportional to an increase in particle fraction. The maximum reduction of about 12% was observed for the largest Re numbers and the maximum particle fraction.

1. Introduction

Owing to their thermophysical characteristics, nanofluids are regarded as a new group of important working media. They are used in solar systems [1], cooling and heating processes, heat exchangers [2–7], chemical industry, power generation equipment, microelectronics, refrigeration and air-conditioning systems [8,9] and in many other devices in which heat and mass transfer processes in nanofluid occur.

While there have been numerous investigations on heat transfer in nanofluids, there is not much data on mass transfer in fluids with suspended nanoparticles. Pang et al. draw attention to this fact in their paper [10] dealing with nanofluids and heat transfer and the nanofluids and mass transfer suggesting what the focus of future research on combined heat and mass transfer in nanofluids should be.

A summary of investigations into mass transfer in nanofluids can be found in the article [11] by Beiki et al. The authors take into account the category of experiment, the kind of nanofluid, the size of nanoparticles and nanoparticle volume concentration. Ashrafmansouri and Estfahany [12] also present a comprehensive review of mass transfer in nanofluids.

In the above reviews it can be found that the application of nanofluids as working media under forced convection conditions enhances heat transfer processes. However, in the case of mass transfer phenomena, ambiguity arises about the role of nanoparticles, as some investigations indicated enhancement, some reduction or no change in mass transfer in nanofluids in relation to base fluids. Therefore further research is required.

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Nomenclature

A	surface area [m^2]
C	ion concentration [$kmol/m^3$]
d	diameter [m]
d_H	hydraulic diameter [m]
D	diffusion coefficient [m^2/s]
F	Faraday constant [96493×10^3 A s/kmol]
h_D	mass transfer coefficient [m/s]
I	current intensity [A]
N	molar flux density [$kmol/(m^2s)$]
$\dot{N}$	ion flux [kmol/s]
L	length [m]
n	valence charge of reacting ions, dimensionless
Re	Reynolds number, $Re = w \cdot d_H/\nu$
Sc	Schmidt number, $Sc = \nu/D$
Sh	Sherwood number, $Sh = h_D \cdot d_H/D$
$\dot{V}$	volumetric flow rate [m^3/s]
w	mean fluid velocity [m/s]
y	normal coordinate [m]

Greek symbols

δ	mean thickness of diffusion layer [m]
μ	dynamic viscosity [Pa·s]
ν	kinematic viscosity [m^2/s]
ρ	density [kg/m^3]
ϕ	volume nanoparticle fraction [%]

Subscripts

a	anode
b	bulk, in the electrolyte
e	electrolyte – base fluid
in	at the inlet
k	cathode
$n\text{-}e$	nano-electrolyte – nanofluid
out	at the outlet
p	nanoparticles

The subject of this study is an experimental investigation into mass transfer during the convective flow of the nanofluid through an annular channel. The application of the annular gap filled with the nanofluid in the special type of coil heat exchanger [4–7] was a motivation of investigations. Studies into convective mass transfer of the nanofluid in an annular channel may also be helpful while investigating heat transfer processes occurring in the exchanger considered.

To obtain the mass transfer coefficients, the electrochemical limiting current technique was used which made direct measurement possible. There is not much literature on the use of the limiting current technique in studies on mass transfer in electrolyte nanofluids. In articles [13–15] the authors present the results of investigations into mass transfer to a rotating disc electrode using the electrolyte with suspended particles of different materials whereas the works [11, 16–18] show the results of electrochemical measurements of mass transfer coefficients during turbulent and laminar flow of the nanofluid through channels of different shape. Sonneveld et al. [13] examined the effect of suspended SiC particles on mass transfer at a rotating disc electrode. The particles tested were larger, having a mean diameter of 3000 nm. Moreover, the fluids considered were characterized by high values of particle volume fractions ranging from about 0.5% to 25%, depending on the particles used. The authors reported the critical values of ϕ, beyond which the presence of the particles in the electrolyte enhanced mass transfer. The critical value in the rotation speed was also determined. Sara et al. [14] investigated the influence of suspended CuO nanoparticles on mass transfer to a rotating disc electrode. Nanoparticle volume fractions of the electrolyte nanofluids used in the experiment ranged from 0.39% to 1.94%. Measurement results showed that adding nanoparticles to the electrolyte increased the mass transfer coefficients. In turn, Liu et al. presented in [15] the results of the rotating disc electrode investigations using the electrolyte-based Al_2O_3 nanofluid with 0.25% mass nanoparticle concentration. The results showed that at a low rotation speed the limiting currents of the electrolyte nanofluids were slightly lower than that of the pure electrolyte. After a further increase in the rotation speed the limiting currents of the nanofluid were higher which meant that mass transfer enhancement occurred. Beiki et al. [11] investigated turbulent mass transfer in a straight circular tube by means of the limiting current technique. The electrolyte nanofluid used was composed of the base electrolyte and TiO_2 or γ-Al_2O_3 nanoparticles. The mass transfer coefficients were measured at 0.005%, 0.01%, 0.015%, 0.025% and 0.05% nanoparticle volume fractions. For lower values of ϕ mass transfer enhanced with the increase in nanoparticle concentration and for higher values of ϕ a decrease in mass transfer was observed. In turn, Beiki et al. present in [16] the results of the research on laminar mass transfer of γ-Al_2O_3/electrolyte nanofluid in a circular tube. As in the previous work the authors observed that the mass transfer coefficients increased with nanoparticle concentration up to an optimum value. For higher values of ϕ the mass transfer coefficients decreased with the nanoparticle concentration increase. Keshishian et al. [17] achieved similar results researching laminar regime. They investigated the effect of silica nanoparticles suspended in the electrolyte on mass transfer in a circular channel. In the case of turbulent flow conditions no changes in the mass transfer coefficients with the nanoparticle concentration increase were observed. Grosicki in [18] considered the possibility of using electrolyte nanofluid mass transfer investigations in the analogous conditions of heat transfer. Mass transfer measurements for 0.01% vol. electrolyte nanofluid flow through a ring-shaped duct were performed. A reduction of mass transfer compared to the base electrolyte for higher values of Reynolds numbers was observed.

In the present work the authors focus on the obtaining the influence of Al_2O_3 nanoparticles on mass transfer coefficients during the convective flow through the annular channel. The volume Al_2O_3 particle fractions: 0.005%, 0.01%, 0.015%, 0.02%, 0.025%, 0.04%, 0.05% and 0.06% have been investigated. Measurements were carried out for Reynolds numbers ranging from 2080 to 10430.

2. Experimental method

2.1. Limiting current technique

The well-known limiting current technique is often applied in the investigation of mass transfer processes. The mentioned above literature positions deal to experiments with nanofluids. In addition to them examples of recent studies on mass transfer in different systems, using limiting current technique, can be found in [19–27].

The method involves observing controlled diffusion of reacting ions at the cathode. Once an external voltage is applied to immersed in the electrolyte the electrodes, the processes of reduction and oxidation occur respectively at the cathode and anode. As a result, the current flows in the external circuit. Magnitude of the current is proportional to the number of ions reacting at the electrode per unit time. According to Faraday's law, the current generated is given by the formula

$$I = nFA_kN \tag{1}$$

In the considered process the ions transport is caused by the