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WALL SHEAR STRESS AT THE MEMBRANE SURFACE AND AT THE SURFACE OF PLEXIGLAS

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The wall shear stress is determined at the surface of a plane ceramic ultrafiltration membrane and at the plate of Plexiglas in a tangential ultrafiltration module. In a first time, the shear stresses are determined at the surface of a plate of Plexiglas mimicking a membrane and at the plane membrane surface without fouling particles with the aim to investigate the influence of permeation. In the second time, the wall shear stress is determined at the surface of the plane membrane during the ultrafiltration of spherical no compressible particles suspension inducting a deposit at the membrane surface. In order to study the influence of the concentration of the particles, two concentrations of particles were used for the experiments. The values of the mean wall shear stress and its fluctuations (turbulent intensity rate) were measured by using an electrochemical method. 20 microelectrodes, on which an electrochemical

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reaction occurs, are mounted flush to the plate of Plexiglas and to the surface of the membrane to determine the maps of shear stress and turbulent intensity rate for two inlet/outlet distributors' configurations.

Introduction

Pressure-driven membrane processes are widely used in numerous industries. Industry generally uses ultrafiltration for many different applications including pre-treatment for other purification systems where organics are not removed (such as ion exchange system), gelatine and protein concentration in the pharmaceutical industry, sugar clarification in the food and beverage industry, cheese whey concentration, oil waste concentration in heavy industrial applications and electronic deposition for paint applications as well as many others.

Permeate flux in pressure-driven membrane processes decreases with time. This flux decline is caused by membrane fouling and concentration polarization at the membrane surface and is the main problem of pressure-driven membrane processes. Transmembrane pressure induces particle accumulation at the membrane surface, usually named the "cake" that can be partially removed by the erosion due to the feed flow. Generally, permeate flux first decreases until a steady-state is reached. This steady-state depends on the hydrodynamic conditions in the membrane system [1]. These hydrodynamics conditions include different parameters (such as the mean cross-flow velocity, the Reynolds number, the shear stress or shear rate at the membrane surface). Among these parameters, the cross-flow velocity is the most frequently used, especially when qualitative influence of the tangential flow in the permeate flux is investigated [2].
But not only hydrodynamics conditions are important. Physico-chemical particle-particle and particle-membrane interactions have substantial effect on the fouling in membrane filtration [3].

Many studies showed that permeation flux, J, governs convective mass transport to the membrane, and wall shear stress rules the transport by erosion, hydrodynamic diffusion or migration of molecules and particles back from the membrane towards the fluid bulk [2,4].

Ziskind and Gulfinger [5] studied the effects of shear and gravity on the motion of small particles in turbulent boundary layers near horizontal and vertical surfaces. Their results show that shear can cause noticeable particle motion normal to the surface, not accounted for when only turbulent effects are considered. It has been shown that inertial motion depends on the shear rate, on the initial distance of the particle from the surface and on the initial particle velocity too.

It is well known that wall suction has a significant effect on mass, momentum and heat transfer rates. From a theoretical viewpoint, wall suction considerably affects the near-wall mean velocities and temperatures.

The wall suction increases the wall shear stress in the suction region and reduces the turbulence levels [6]. Sofialidis and Prinos [6] studied the effects of wall suction on fluid flow and their results indicate the following: wall suction has a significant effect on mass and heat transfer rates. The laminar sublayer is shown to decrease with increasing wall suction. Wall suction tends to decrease the levels of the turbulent shear stress, indicating that reverse transition from turbulent to laminar flow takes place for a longer suction length.

The aim of the present work is to map the values of the mean wall shear stress and its turbulence intensity on a plane sheet of Plexiglas mimicking a membrane and on the surface of the membrane with and without deposit. In previous papers [7–10], the influence of the inlet/ outlet configurations and the incidence of the design of the distributors on the wall shear stress at the surface of a plate of Plexiglas (without permeation) and at the surface of a membrane were studied. Therefore, we used only two configurations of distributors — B (six distributors of same diameter d = 5mm), J (distributor of "pseudo-trapezoidal" shape), which were the best compromise between the wall shear stress values and turbulent intensity rate.

The experiments were carried out in the range of Reynolds numbers from 3300 – 6100 (transition flow regime).

Theory

Determination of Shear Stress and Turbulent Intensity Rate

The experimental determination of shear stress at the surface of a Plexiglas plane and at the surface of a plane ceramic ultrafiltration membrane was carried out using an electrochemical method. Twenty microelectrodes were mounted flush to the surface of Plexiglas and the membrane. On the microelectrode surface occurs the electrochemical reaction which is based on the reduction of the ferricyanide ion on the cathodic surface. The reverse reaction takes place at the anode.

$$\text{Cathode} \quad Fe(CN)_6^{3-} + e^- \leftrightarrows Fe(CN)_6^{4-}$$

$$\text{Anode} \quad Fe(CN)_6^{4-} \leftrightarrows Fe(CN)_6^{3-} + e^-$$

The anode is made of nickel, the cathode is made of platinum.

The reaction was conducted at voltage high enough to reduce the concentration of the reacting species to zero at the surface (limiting diffusional conditions). Under these conditions, the rate of reaction is controlled by the rate of mass transfer (in this case driven by diffusion only). Thus, the mass transfer coefficient, k, between the electrolyte and the probe surface is related to the

limiting diffusional current, I_L, as follows

$$I_L = \nu_e F \frac{\pi d_e^2}{4} C_0 k \tag{1}$$

where ν_e is the number of electrons involved in the electrochemical reaction ($\nu_e = 1$), F is Faraday's constant, d_e is the electrode diameter, and C_0 is the bulk concentration of the ferricyanide ions.

The solution to the diffusion-convection equation and the different assumptions are described in a previous work [7].

For a circular probe embedded in an inert wall, the wall transfer coefficient is related to the mean wall velocity gradient $\bar{S}$ at steady- state conditions [11] by the equation

$$k = 0.862 \left(\frac{D^2 \bar{S}}{d_e} \right)^{1/3} \tag{2}$$

Combining Eqs (1) and (2), the mean wall velocity gradient can be determined and then the wall shear stress can be calculated by

$$\tau = \mu \bar{S} \tag{3}$$

where μ represents the dynamic viscosity of the electrolytic solution.
The turbulent intensity rate, T_s, defined by Eq. (4), is used to quantify the velocity gradient fluctuations,

$$T_s = \frac{\sqrt{\overline{s^2}}}{\bar{S}} \tag{4}$$

where s represents the fluctuating velocity gradient and $\bar{S}$ the mean velocity gradient, following the decomposition

$$S(t) = \bar{S} + s(t) \quad \text{with} \quad \overline{s(t)} = 0 \tag{5}$$

This turbulent intensity rate is calculated by integrating the velocity gradient power density spectrum, $W_{SS}(f)$, derived from the measured spectrum, $W_{ii}(f)$, of the current fluctuations with the following equation

$$W_{ii}(f) = |H(f)|^2 W_{SS}(f) \tag{6}$$

where $|H(f)|$ is the amplitude of the transfer function [12].

Determination of the Electrodes Diameters

The electrode diameter is measured by using a voltage-step transient technique [13]. This method is based on the study of the transient response of the electrodes to a voltage step from 0 to the diffusional plateau potential. This calibration is interesting for electrodes located inside the module because it can be carried out at real experimental conditions; moreover, it does not require any knowledge of local hydrodynamics.

Experimental

Electrolytic Solution

The electrolytic solution was a mixture of potassium ferricyanide (2 mol m^{-3}), potassium ferrocyanide (50 mol m^{-3}), and potassium sulphate (100 mol m^{-3}). The potassium sulphate acts a low resistance vehicle for current flow and ensures that the transfer at the cathodic surface is only controlled by diffusion. At a working temperature of 30 °C, the diffusion coefficient of the ferricyanide ions is 8.36×10^{-10} $m^2 s^{-1}$, the density is 1023 kg m^{-3} and the kinematic viscosity is 0.82×10^{-6} $m^2 s^{-1}$.

Particles for Filtration and Suspension

The suspension consisted of spherical microparticles, made from borosilicate. The density of the glass particles was 1100 kg m^{-3} and the diameter was 8 – 11 μm. The ultrafiltration was carried out with two concentrations of particles, 5 and 10 g l^{-1}.

Cross-flow Ultrafiltration Unit, Membrane and Plexiglas

The ultrafiltration unit (Fig. 1) has internal dimensions of 122 mm length and width and 1mm channel height. The channel Reynolds number is defined by

$$Re = \frac{U_0 d_H}{\nu} \tag{7}$$

where $d_H = 2e$ (e is the height of channel), U_0 is the mean velocity in the channel defined by

$$U_0 = \frac{Q}{Le} \tag{8}$$

where Q represents the volumic flow rate and L the length of the module. The channel Reynolds number was varied from 3300 to 6100.

The used ceramic plane ultrafiltration membrane, commercialized by TAMI INDUSTRIES SA (NYONS, FRANCE), has a 150 kDa molecular weight cut-off and a total surface area of 0.015 m^2. The support was alumina/silicate and the filtering layer titanium oxide. The membrane and the Plexiglas plate had the same size (122 ×122 mm).

Twelve cathodic microelectrodes were mounted flush to the plate of Plexiglas and 20 cathodic microelectrodes were mounted flush to the plane ceramic ultrafiltration membrane. The plate of Plexiglas was rotated by 180° for a second experiment. Thus we had twenty positions of microelectrodes and a comparison with twenty positions of membrane cathodic microelectrodes.

A nickel plate, acting as the anode, was inserted at the top of the module. The cathodic microelectrodes were made of platinum wire 0.4 mm in diameter. A potential difference of –400 mV was applied between the anode and the cathodes in order to ensure limiting diffusional conditions at the microelectrodes surface (diffusional limiting plateau).

Distributors

Two designs of distributors (B and J) described in the previous work [10] have been chosen (Fig. 2). B- Six distributors of same diameter $d = 5$, J- distributor of "pseudo-trapezoidal" shape.

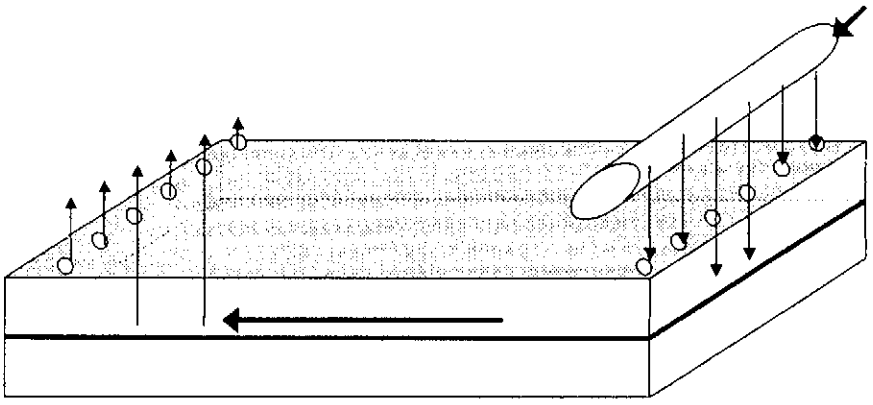

Fig. 1 Plane ultrafiltration module

Distributors shape	Description
	6 distributors of same diameter d= 5 mm
	distributor of "pseudo trapezoidal" shape

Fig. 2 Description of the two distributors investigated

Experimental Set-up

The particles suspension, placed in a 10 l stirred tank was kept at 30 °C. The fluid was brought to the circuit by a centrifugal- type pump to ensure a constant tangential velocity at the plane surface. The flow rates were measured using a rank of two flowmeters. The filtration could be conducted under constant differential pressure conditions of 50 kPa, using a second pump and a pressure throttling valve installed on the outlet side of the membrane module. The permeate and the retentate were returned to the feed tank to keep a constant concentration of

particles during ultrafiltration processes.

The experiments were conducted under nitrogen, because oxygen reacts cathodically at a voltage near that used in the experiments.

Experimental data were stored on a digital audio tape (DAT) and transferred to a computer to be analyzed by means of the signal processing software LABVIEW. For each Reynolds number at stationary state, the limiting diffusional current was recorded during one minute and the local wall shear stress considered further is an average of all the values recorded during this time. The experiments were performed twice for each distributor and the results presented are the average of these two experiments.

Results and Discussion

The knowledge of the electrode diameters inserted in the membrane and in the Plexiglas is necessary to determine the local wall velocity gradient. Ten experiments were performed for each probe. The electrode diameter was, for all electrodes, close to the platinum wire diameter (400 μm); the difference is caused by operations, which were used for implementation at the plate surfaces of Plexiglas and of the membrane.

Using the electrode diameter and the limiting diffusional current values, the local wall shear stresses can be determined for different Reynolds numbers. The values of wall shear stress were measured in the range of Reynolds numbers from 3300 to 6100 (beginning of turbulent flow-regime).

Figure 3 represents the wall shear stress values versus the electrodes position on the plate of Plexiglas (system without suction) and at the membrane surface without deposit (system with suction) for the distributors B a J and for the Reynolds number of 6109.

For both distributors B and J the system without suction (Plexiglas) exhibits two zones of low shear stress near the module walls and a zone of high shear stress in the middle of the plate (Fig. 3).

At the membrane surface, the values of wall shear stress are much higher. These experimental results confirm conclusions about the influence of suction effects on the wall shear stress [6]. At the membrane surface, there exists small zone of very high shear stress near the module outlet and small zone of very low shear stress close to the module inlet. The same zones are obtained for both distributors.

Table I represents the evolution of the mean wall shear stress for all the systems investigated. It is evident that the values of average wall shear stress increase with increasing Reynolds number irrespective of the type of distributor or the presence and absence of suction effects.

If we compare the results of average wall shear stress at the Plexiglas sur-

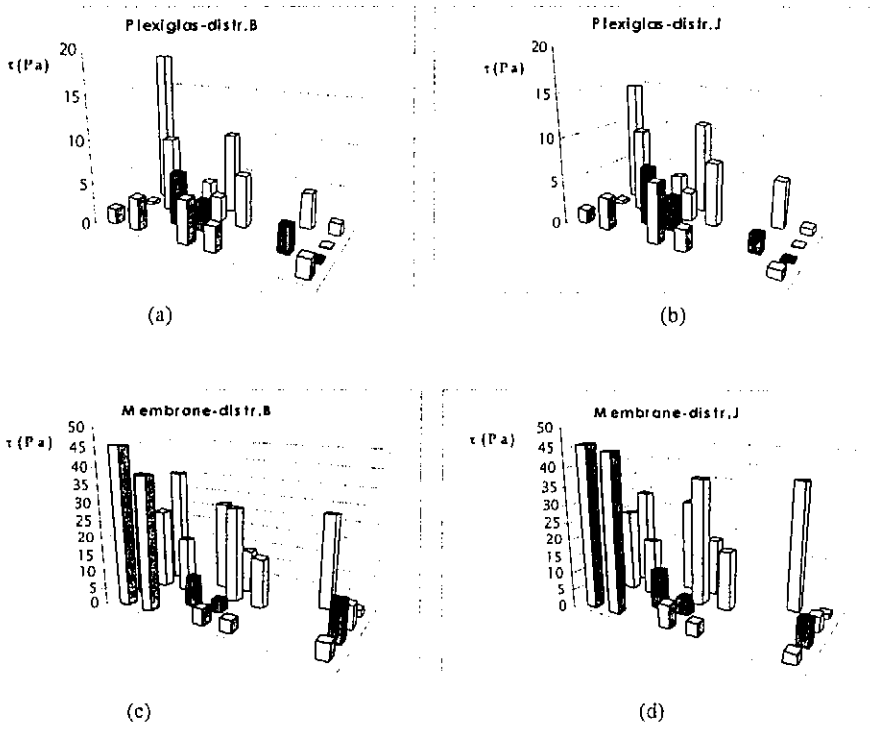

Fig. 3 Local wall shear stress versus the electrode position, Re = 6109, a) Plexiglas + distributor B, b) Plexiglas + distributor J, c) membrane + distributor B, d) membrane + distributor J

Table I Average wall shear stress

Re	τ, Pa			
	Distributor B		Distributor J	
	Plexiglas	Membrane	Plexiglas	Membrane
3332	1.95	12.66	1.90	7.88
3887	2.29	14.06	2.25	10.01
4442	2.73	15.36	2.68	14.52
4998	3.17	16.46	3.23	16.37
5553	3.65	19.31	3.77	20.20
6108	4.28	22.90	4.30	23.68

face for both distributors, we can see that the values of the wall shear stress are almost the same for all of the Reynolds numbers. For the values of wall shear stress at the membrane surface the differences are higher and the influence of the kind of distributor is visible. But with increasing Reynolds number the differences between the distributors diminish.

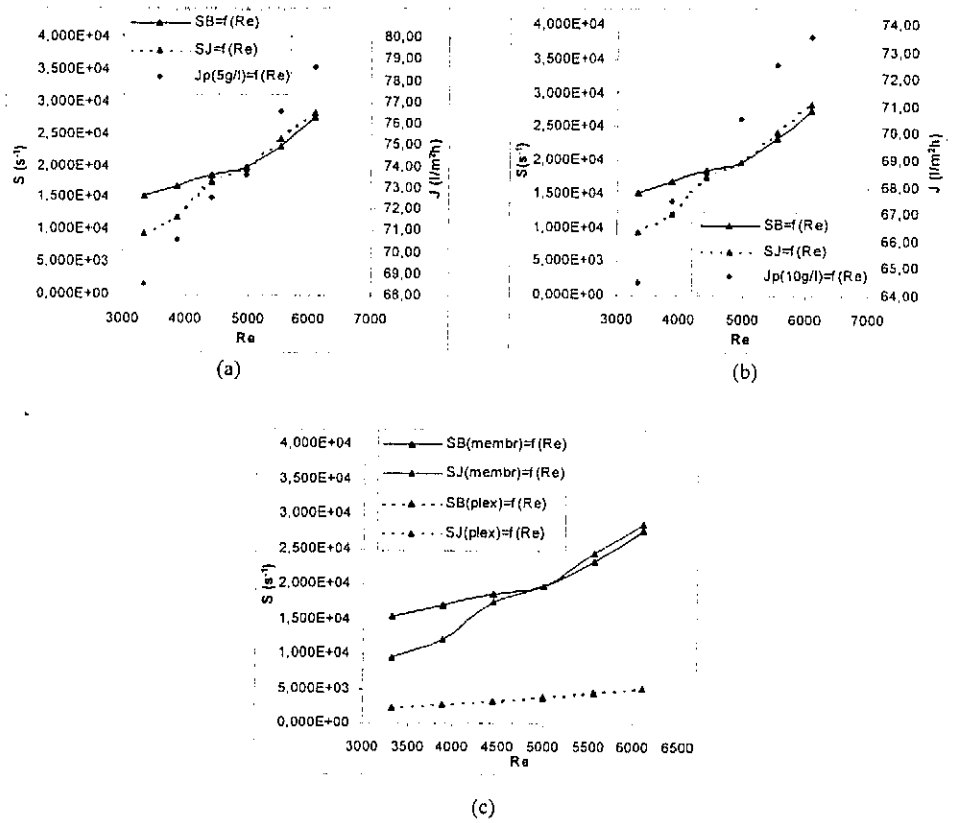

Fig. 4 a) Average wall shear stress rate at the membrane surface without deposit and permeation flux for particle concentrations 5 g l^{-1} for distributors B and J as a function of *Re*
b) Average wall shear stress rate at the membrane surface without deposit and permeation flux for particle concentrations 10 g l^{-1} for distributors B and J as a function of *Re*
c)Average wall shear stress rate at the membrane surface without deposit and at the Plexiglas surface for distributors B and J as a function *Re*

Figure 4 represents the evolution of the average wall shear rate at the surface of the membrane without deposit and for the Plexiglas surface calculated for the twenty microelectrodes. In Fig. 4 we took the values of average wall shear rate for the membrane surface without deposit instead of the wall shear rate values

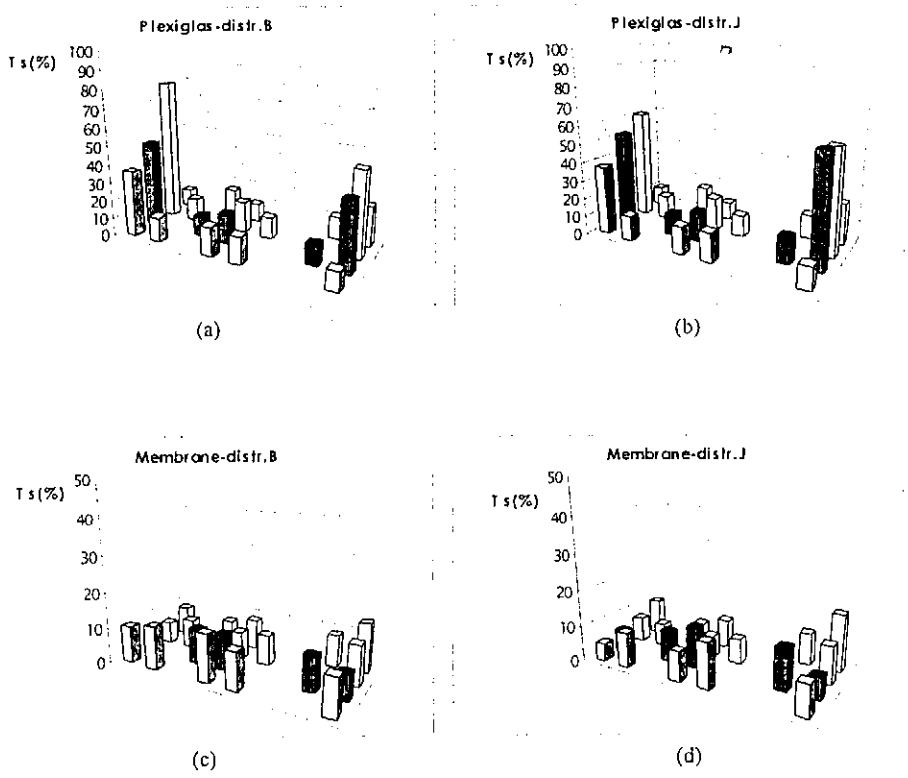

Fig. 5 Local turbulent intensity rate of velocity gradient versus the electrode position, Re = 6109: a) Plexiglas + distributor B, b) Plexiglas + distributor J, c) membrane + distributor B, d) membrane + distributor J

obtained with deposit. We can replace these values because the previous work of Cecile Gaucher [3] showed that for Reynolds numbers higher than 416 the values of the average wall shear rate with and without deposit of particles are not significantly different. In Figs 4a, b, there are the average values of wall shear rate obtained at the membrane surface without deposit and the permeate flux (particles concentration 5 g l^{-1} — Fig. 4a, particles concentration 10 g l^{-1} — Fig. 4b) as a function of the Reynolds number. With the increasing Reynolds number the permeate flux for both particles concentrations increases (see Figs 4a, b). The permeate flux is not affected by the type of distributor for any of the particles concentrations. It is sure, that the thickness of the deposit for particle concentration 10 g l^{-1} will be, for the same Reynolds numbers, higher than for the particle concentration 5 g l^{-1}. Gesan-Guizion *et al.* [14] found out that the higher the wall shear stress, the lower the deposited mass and the thickness; so we can assume that the values of the mean wall shear stress for particles concentration 10 g l^{-1}

Table II The average turbulent intensity rate of the velocity gradient

Re	T_s, %			
	Distributor B		Distributor J	
	Plexiglas	Membrane	Plexiglas	Membrane
3332	10.36	22.74	12.09	24.05
3887	10.26	22.79	11.26	24.66
4442	10.62	23.12	10.43	24.70
4998	10.72	23.34	10.53	24.97
5553	11.00	24.47	8.88	25.65
6108	9.40	25.63	8.69	27.08

will be lower than the mean wall shear rate for concentration 5 g l^{-1}. From Fig. 4c, it is apparent that the velocity gradient values for the membrane surface are, for both distributors, larger than values of velocity gradient observed for the Plexiglas surface. In this way the influence of the suction effects is visible.

Figure 5 represents the maps of turbulent intensity rate of the velocity gradient for the two distributors, B and J.

The turbulent intensity rates obtained without permeation are higher near the inlet/ outlet sections; this is mainly due to the wall effects that cause a higher turbulence level in this part of the cell.

The turbulent intensity rates obtained with permeation (membrane without particles) are more homogeneous; no different zones can be observed. The turbulent intensity rate with permeation (membrane without particles) is lower than that obtained without permeation. This decline of the turbulent intensity values is caused by the suction effects, which is in agreement with the results published in literature [6] emphasizing the laminarization of the wall-flow due to the suction.

The average values of turbulent intensity rates at the surface of membrane and Plexiglas, for Reynolds number from 3332 to 6109, calculated for the twenty microelectrodes are shown in Table II. For both distributors the average value of turbulent intensity rate at the membrane surface decreases with increasing Reynolds number. This fall is due to the suction effects at the membrane surface. For both distributors the average value of turbulent intensity rate at the Plexiglas surface increases with increasing Reynolds number, which corresponds to literature [2].

Conclusion

The experimental data discussed in this paper show the values of the mean wall shear stress and the turbulent intensity rate at the surface of the plane plate of Plexiglas (without permeation) and at the surface of a plane ceramic ultrafiltration membrane (with permeation) in the range of Reynolds numbers from 3300 – 6100. The results show that there is heterogeneity in the local values of the mean wall shear stress and the turbulent intensity rate. The comparison of the mean wall shear stress and the turbulent intensity rate determined at the surface of a plane plate of Plexiglas (without permeation) and at the surface of a plane ceramic ultrafiltration membrane (with permeation) show that the mean wall shear stress at the membrane surface is higher than at the Plexiglas surface, and that the turbulent intensity rate at the membrane surface is lower than that obtained at the surface of the Plexiglas. From these results the influence of the suction velocity is evident.

The present work forms a continuation to the work by Cecile Gaucher at lower Reynolds numbers — the range from 140 to 3470. In the preliminary measurements, the results and conclusions were confirmed, and in the experiment itself, they were extended into a range of the Reynolds numbers from 3300 to 6100.

Acknowledgements

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Symbols

C_0 bulk concentration of ferricyanide ions, mol m^{-3}
d_e electrode diameter, m
d_H hydraulic diameter of the cell, m
D diffusion coefficient of ferricyanide ions, $m^2 s^{-1}$
e channel height, m
F Faraday's constant (F = 96500 C mol^{-1})
I_L limiting diffusional current, A
k mass transfer coefficient, m s^{-1}
L channel length, m
Q volumetric flow, $m^3 s^{-1}$
Re Reynolds number
$S(t)$, S, $s(t)$ instantaneous, average and fluctuating velocity gradients, s^{-1}

T_s turbulent intensity rate
U_0 mean velocity in the cell, m s^{-1}
W_{ii} power spectral density of the fluctuating current, A^2 s
W_{SS} power spectral density of the velocity gradient, s^{-1}

Greek letters

μ dynamic viscosity, Pa s
ν kinematic viscosity, $m^2 s^{-1}$
ν_e number of electrons involved in the electrochemical reaction
τ wall shear stress, Pa

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