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Application of Mass/Heat Transfer Analogy in the Investigation of Convective Heat Transfer in Stationary and Rotating Short Minichannels

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1. Introduction

Convective heat transfer during laminar fluid flow through channels is an important technological problem. The literature provides much research data on heat transfer phenomena occurring during fluid flow through channels of different dimensions and shapes based on theoretical analysis, numerical calculations and experimental investigations. Theoretical analysis has attempted to solve the problem of convective heat transfer in channels of basic shape in simplified conditions of fluid flow. Laminar convective heat transfer in pipes where the fluid velocity profile was parabolic was described by Graetz (Graetz, 1885). His solution to this classical problem was further developed by Sellars, Tribus and Klein (Sellars et al., 1956). Alternatively, Levěque (Levēque, 1928) investigated heat transfer in the entrance region of pipes where hydraulic stabilisation occurs. All these works offer an analytical solution to the problem. Numerical investigation of heat transfer in the entrance region of pipes was initiated by Kays (Kays, 1955) who provided the results of numerical calculations for three types of gas flow conditions: uniform wall temperature, uniform heat flux and uniform difference between wall and fluid temperature. On the other hand, the work of Sider and Tite (Sider and Tite, 1936) is an example of an early experimental investigation where an empirical formula for the heat transfer coefficient calculations, regardless of the fluid being heated or cooled, is provided.

The above-mentioned works were followed by further research on the laminar convective fluid flow in channels. Particularly, heat transfer in channels of small hydraulic diameters was extensively investigated. It turned out that heat transfer and fluid flow in small diameter channels often differed from those in channels of conventional dimensions. Mathematical equations describing heat transfer cannot always be applied to mini- or micro-channels. Hence some researchers (Adams et al., 1998), (Tso and Mahulikar, 2000), (Owhaib and Palm, 2004), (Lelea et al., 2004), (Celata et al., 2006), (Kandlikar et al., 2006), (Yang and Lin, 2007), (Yarin et al., 2009) examined liquid and gas convective heat transfer in circular mini- and micro-channels using experimental methods, mostly the thermal balance method. However, the surface and fluid temperature measurements using this method are difficult to obtain due to the small size of the channels tested. Application of mass transfer investigations and the mass/heat transfer analogy makes it possible to avoid the problem as it excludes temperature measurements. In this chapter application of the mass/heat transfer

analogy in the study of heat transfer in short minichannels is described. The electrochemical technique is employed in measuring the mass transfer coefficients.

2. Mass/heat transfer analogy

The heat transfer coefficient is most often determined by quite intricate experiments based on the thermal balance method which requires complex instruments and sometimes difficult measurements. An alternative method of obtaining it is to measure it by applying the mass/heat transfer analogy. There is an exact analogy between the mass and heat transport processes so mass transfer results may be converted to heat transfer results. This depends on the similarity of the equations describing the heat and mass change processes. If the boundary conditions are the same for a given geometry, the differential equations have the same solution. For the mass transfer related to a forced convection, the solution to the problem is given by the general correlation

$$Sh = Sh(Re, Sc), \quad (1)$$

analogously, for heat transfer

$$Nu = Nu(Re, Pr), \quad (2)$$

where: Nu – Nusselt number, $h \cdot d_h / k$; Re – Reynolds number, $w \cdot d_h / \nu$;
 Pr – Prandtl number, ν / a ; Sc – Schmidt number, ν / D ;
 Sh – Sherwood number, $h_D \cdot d_h / D$; a – thermal diffusivity [m^2/s];
 d_h – hydraulic diameter [m]; D – mass diffusion coefficient [m^2/s];
 h – heat transfer coefficient [$W/(m^2K)$]; h_D – mass transfer coefficient [m/s];
 k – thermal conductivity [$W/(mK)$]; w – mean fluid velocity [m/s];
 ν – kinematic viscosity [m^2/s].

In the case when the forced convective heat transfer occurs during rotation, the Rossby number has to be introduced into Eqs (1) and (2), thus

$$Sh = Sh(Re, Ro, Sc) \quad (3)$$

and

$$Nu = Nu(Re, Ro, Pr), \quad (4)$$

where: Ro – Rossby (rotation) number, $\omega \cdot d_h / w$; ω – angular velocity [rad/s].

The results of the experimental investigation of the mass change processes may be correlated in the empirical equation

$$Sh = c Re^p Sc^q, \quad (5)$$

where c, p, q – empirical constants.

Taking into account the mass/heat transfer analogy, the results of the heat transfer processes may be correlated in the form

$$Nu = c Re^p Pr^q. \quad (6)$$

The analogy requires that the Sc and Pr numbers be equal. However, the similarity of the fluid properties expressed by the equal Schmidt and Prandtl numbers is very difficult to obtain. Nevertheless, the research data (Goldstein & Cho, 1995) show a good agreement of the mass transfer experimental results with heat transfer results for different Sc and Pr numbers.

Based on equations (5) and (6) the mass transfer measurement results may be converted to the heat transfer formula

$$\frac{Nu}{Sh} = \left(\frac{Pr}{Sc}\right)^q \quad (7)$$

In the Chilton-Colburn analogy, the experimentally obtained exponent $q = 1/3$ (Chilton & Colburn, 1934). The authors present the analogy in the form:

$$j_M = St_M Sc^{2/3} \quad (8)$$

$$j_H = St_H Pr^{2/3} \quad (9)$$

$$j_M = j_H \quad (10)$$

where: j_H, j_M - Chilton-Colburn coefficients for heat and mass transfer,

St_H - Stanton number for heat transfer, $h/(c_p \cdot \rho \cdot w)$,

St_M - Stanton number for mass transfer, h_D/w ,

c_p - specific heat capacity [J/(kgK)],

ρ - density [kg/m³].

According to this description some of the researchers (Bieniasz and Wilk, 1995), (Bieniasz 1998), (Wilk, 2004), (Bieniasz, 2010) present the results of the mass transfer measurement as

$$j_M = p Re^q \quad (11)$$

When rotary conditions are involved, the analogy between mass forces is maintained by Rossby number equality. In this case the Rossby number can occur as a parameter in the equations describing mass or heat transfer. Bieniasz (Bieniasz, 2010) proposes the following correlation describing mass transfer in rotary conditions:

$$j_M = p_1 Re^{q_1} + p_2 Re^{q_1} Ro, \quad (12)$$

where: p_1, p_2, q_1, q_2 - empirical constants.

3. Experimental technique of the mass transfer coefficient measurement

The limiting current method and naphthalene sublimation are basic experimental techniques which may be used for mass transfer coefficient measurements.

Using naphthalene sublimation involves the following stages (Goldstein and Cho, 1995):

- preparing the coat test models with naphthalene,
- measuring the initial naphthalene surface profile or weight,
- conducting the experiment with a naphthalene-coated model,

- measuring the naphthalene surface profile or weight after the mass change experiment,
- calculating the mass transfer coefficient. The coefficient is given by the equation

$$h_D = \frac{\Delta m}{(\rho_{VN,w} - \rho_{VN,f})\tau}, \quad (13)$$

where: Δm - surface mass decrement of naphthalene [kg/m²],
 $\rho_{VN,w}$ - naphthalene vapour density on the surface [kg/m³],
 $\rho_{VN,f}$ - naphthalene vapour density in the fluid [kg/m³],
 τ - time of the experiment [s].

Recently, naphthalene sublimation has been often used (Szewczyk, 2002), (Kim and Song, 2003), (Hong and Song, 2007), mainly because mass transfer coefficients can be determined by this method with high accuracy. Moreover, based on the mass transfer coefficients obtained, and using mass/heat transfer, reliable results for heat transfer coefficients can be achieved.

However, naphthalene sublimation cannot be applied in all flow and geometric conditions (Goldstein and Cho, 1995). Another technique used to determine heat transfer coefficients by mass/heat transfer analogy is the limiting current method. This method involves observing the controlled ion diffusion at one of the electrodes, usually the cathode. Once the external voltage is applied to the electrodes which are immersed in the electrolyte, electric current arises in the external circuit. According to Faraday's law, the magnitude, I , of the current generated is given by

$$I = iA = nFAN, \quad (14)$$

where: A - surface area of the cathode [m²],
 F - Faraday constant [96 493 A s/kmol],
 I - current in the circuit [A],
 i - current density [A/m²],
 N - molar flux density [kmol/(m² s)],
 n - valence charge of reacting ions.

In this process ion transport is caused by convection, migration and diffusion. The convection element is small. If it is ignored, the error is not greater than 0.3% (Bieniasz, 2005). Reduction of the migration element can be achieved through adding a background electrolyte to the electrolyte investigated. If only the diffusion process is taken into account, the molar flux density according to Fick's law is given by:

$$N = -D \frac{dC}{dy}, \quad (15)$$

where: dC/dy - gradient of the reacting ions concentration,
 C - ions concentration [kmol/m³],
 y - normal coordinate [m].

Then, based on the Nernst model (linear dependence of ion concentration vs the distance from the electrode surface in the diffusion layer - Fig.1), one may write:

$$\frac{dC}{dy} = \frac{C_b - C_w}{\delta}, \quad (16)$$

$$\delta = D/h_D, \tag{17}$$

where: C_b - bulk ions concentration [kmol/m³],
 C_w - ions concentration at the electrode surface [kmol/m³],
 δ - mean thickness of Nernst diffusion layer [m].

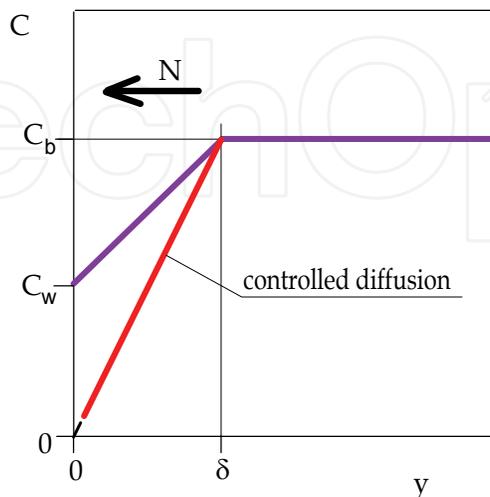


Fig. 1. Ion concentration distribution in the electrolyte at the cathode surface

On the basis of the equations (14) - (17) one can obtain

$$i = nFh_D(C_b - C_w). \tag{18}$$

It is impossible to calculate the mass transfer coefficient from equation (18) because C_w is practically non-measurable. In the limiting current method an increasing current is caused to flow across the electrodes by increasing the applied voltage until a characteristic point is reached - point A in Fig. 2. If the anode surface is much bigger than the cathode surface, a further increase in the applied voltage will not lead to increased current intensity - segment AB in Fig.2. This is the limiting current plateau. Under these conditions the ion concentration at the cathode surface C_w approaches zero. Based on the measurement of the limiting current I_p , the mass transfer coefficient can be calculated from the equation

$$h_D = \frac{I_p}{nFAC_b}. \tag{19}$$

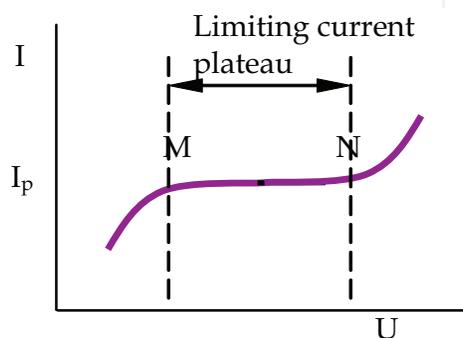


Fig. 2. Typical polarization curve

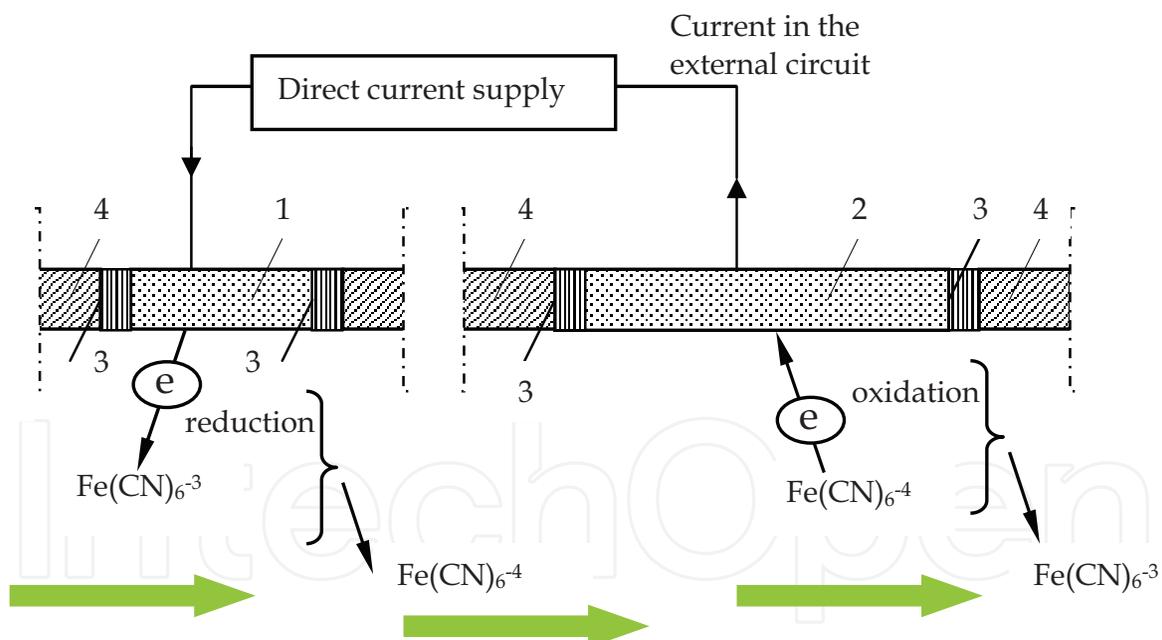
The polarization curve in Fig. 2 shows three zones: zone $\rightarrow A$ where the primary reaction is under mass transport and electron transfer control, plateau zone $A \leftrightarrow B$ where the primary reaction is controlled by mass transport-controlled convective-diffusion, and zone $B \leftarrow$ where a secondary reaction occurs at the same time as the primary reaction. When employing the limiting current method it is important to fulfil the following conditions (Szántó et al., 2008):

- the electrode should be carefully polished before each experiment,
- the electrode should be activated before the experiment,
- the background electrolyte should provide stable limiting current measurement over a long time,
- the electrolytes should be freshly prepared before each experiment and investigations should be performed in the absence of direct sunlight.

4. Experimental investigations

4.1 Properties of the electrochemical system applied

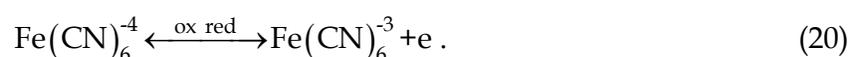
Measurements of the mass transfer coefficients were performed using the ferrocyanide/ferricyanide redox couple at the surface of nickel electrodes immersed in an aqueous solution of equimolar quantities of $K_3Fe(CN)_6$ and $K_4Fe(CN)_6$. A molar solution of sodium hydroxide NaOH was applied as the background electrolyte.



Electrolyte - aqueous solution of equimolar quantities of $K_3Fe(CN)_6$ and $K_4Fe(CN)_6$. and molar solution of sodium hydroxide NaOH; 1 - nickel cathode; 2 - nickel anode; 3 - electric insulation; 4 - construction element

Fig. 3. Scheme of the electrochemical process.

The oxidation-reduction process under the convective-diffusion controlled conditions is written as:



Besides the redox couple described by eq. (20), an unwanted redox couple shown in the equation below may take place:

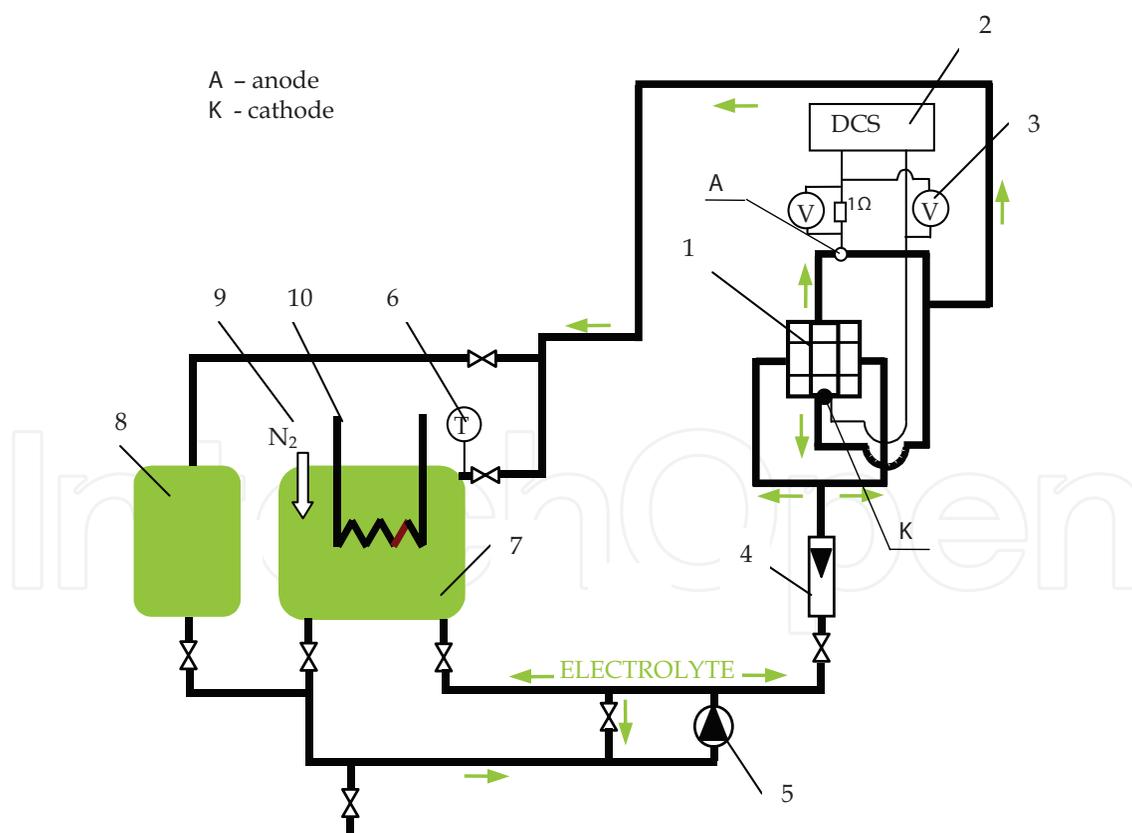


In this case the limiting current is the sum of the limiting current of the reduced $\text{Fe}(\text{CN})^3$ ions and oxygen. It was therefore necessary to eliminate the dissolved oxygen from the electrolyte by washing it with nitrogen.

Fig.3. shows the electrochemical system used in the experiment. The physical properties of the electrolyte at 25°C were as follows: $D = 6.71 \times 10^{-10} \text{m}^2/\text{s}$, $\nu = 1.145 \times 10^{-6} \text{m}^2/\text{s}$ (Wilk, 2004). The value of ferricyanide ion concentration was measured using iodometric titration. The concentration of ferricyanide ions changed over time (Szanto et al., 2008), its sample value during measurements being $3.52 \times 10^{-3} \text{kmol}/\text{m}^3$.

4.2 Experimental rig

The measurements of limiting current were performed using a universal rig. Its electrolyte as well as its nitrogen and electrical measurement system are shown in Fig.4. The anode was located behind the cathode in the direction of the electrolyte flow. Because the purpose of the experiment was to achieve controlled diffusion at the cathode, the necessary condition anode surface \gg cathode surface had to be fulfilled.



1 - test section, 2 - direct current supply, 3 - voltage measurement, 4 - flow rate measurement, 5 - pump, 6 - temperature measurement, 7 - main tank of electrolyte, 8 - tank for activation, 9 - nitrogen bubbling, 10 - preheater.

Fig. 4. Scheme of the experimental rig.

The measurement stand made it possible to carry out the following stages of the experiment: cathode activation, stabilisation of the electrolyte temperature at 25°C and its measurement, release of oxygen from the electrolyte by nitrogen bubbling, step alteration and measurement of the external voltage applied to the electrodes and measurement of the electric current in the external circuit. The test section mounted on the rig enabled measurements to be made during rotation.

5. Convective mass transfer in circular minichannels

5.1 Stationary conditions

The experiment was performed in circular minichannels of $d=1.5$ mm inner diameter and of $L=15$ mm length. Measurements were made using a PVC ring with 600 radially drilled identical minichannels. The ring used for the measurements was part of the test section prepared and used previously in investigations on the rotor of a high-speed regenerator (Bieniasz and Wilk, 1995), (Wilk 2004), (Bieniasz, 2009), (Bieniasz, 2010). Nickel cathodes were mounted as the inner surfaces of three minichannels. A scheme of the ring with the minichannels and electrolyte flow direction is shown in Fig. 5.

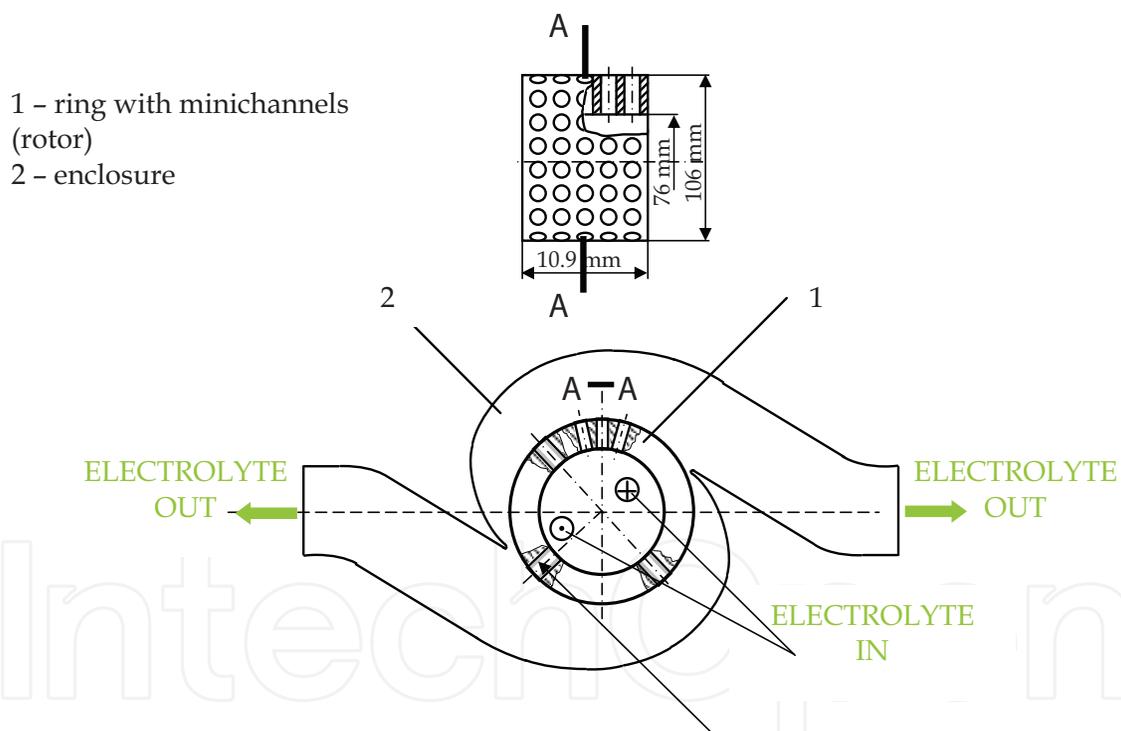


Fig. 5. Simplified scheme of part of the test section for the investigations of the mass transfer coefficient in short circular minichannels.

Before the experiment the inner surfaces of the minichannels were polished using a greasy diamond abrasive compound. After polishing the surface roughness was about $0.012\mu\text{m}$ so the investigated minichannels were considered smooth (Kandlicar et al., 2001).

As a result of the experiment, linear sweep voltammograms of ferricyanide ion reduction at the cathode were obtained. Examples of the voltammograms for one of the investigated cathodes (inner surface of the minichannel) with the Reynolds number as a parameter are shown in Fig. 6.

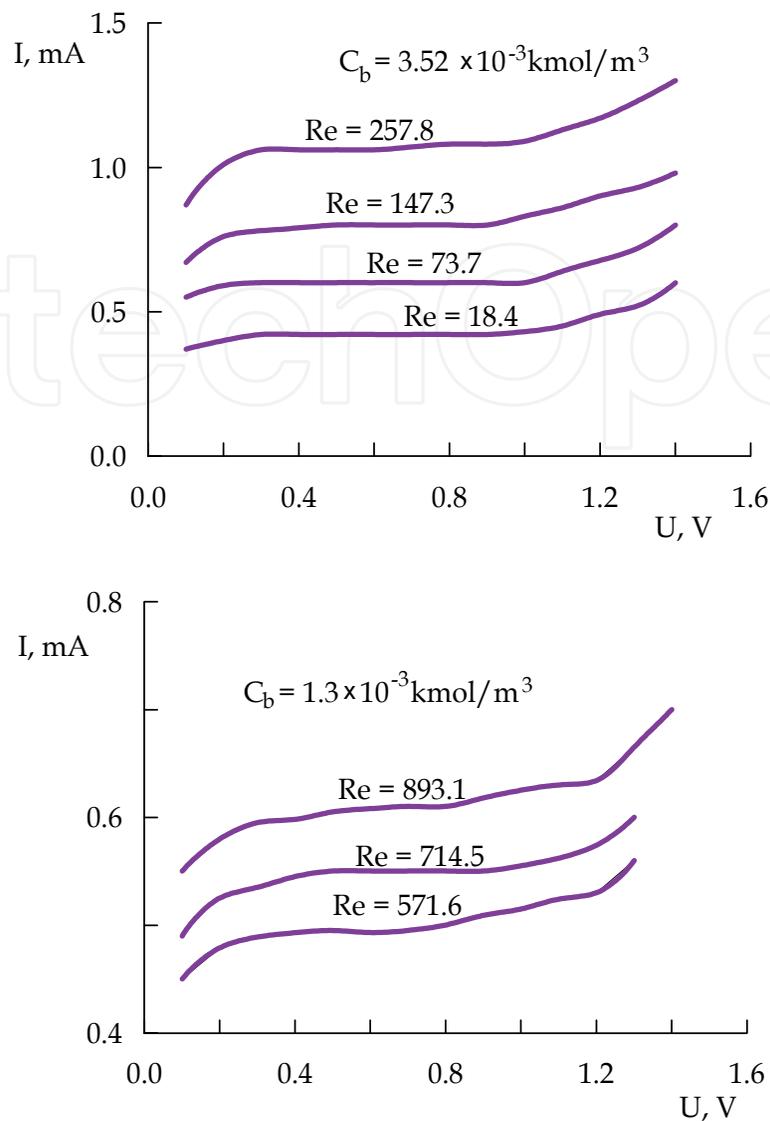
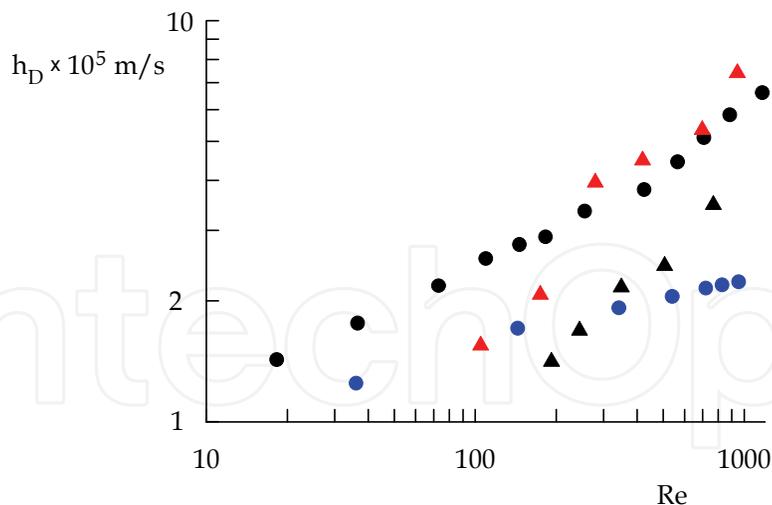


Fig. 6. Examples of the limiting current plateau at different Reynolds numbers and different bulk ion concentrations

The values of the Reynolds numbers were calculated based on the flow rate measured. The volumetric flow rate through a single minichannel was calculated as the ratio of the total measured rate to the number of minichannels. The assumption about an identical flow rate in all the minichannels was based on a theoretical analysis of the flow through the rotor (ie the ring with minichannels) (Bieniasz, 2009) and the assumption that all the channels had identical inner diameters.

As the final result of the experiment the mean mass transfer coefficient at the inner surface of the circular short minichannel was calculated from eq. (19). The necessary limiting current plateau was obtained as the average value of the values I_p measured for all the cathodes investigated. The plot of the mean mass transfer coefficient vs. the Reynolds number is shown in Fig. 7.

The results were compared with those from the literature data concerning the mass transfer coefficients in mini or microchannels obtained using the electrochemical limiting current method.



• - this study, $d = 1.5$ mm, $L = 15$ mm; • - (Sara et al., 2009), circular microchannel, $d = 0.205$ mm, $L = 20.22$ mm; ▲ - (Bieniasz and Wilk, 1995), irregular curved minichannel, $d_h = 2.46$ mm, $L = 15.8$ mm; ▲ - (Bieniasz and Wilk, 1995), irregular curved minichannel, $d_h = 1.34$ mm, $L = 15.8$ mm

Fig. 7. Results of mass transfer coefficient measurements

Application of the limiting current method made it possible to perform preliminary investigations of the mass transfer coefficient distribution along the short minichannel. Additional cathodes were used in the measurements. They were of nickel and of length $1/4L$ and $3/4L$. The shorter cathodes were located as inner surfaces of the minichannels. Examples of voltammograms for the $3/4L$ length cathode are shown in Fig. 8.

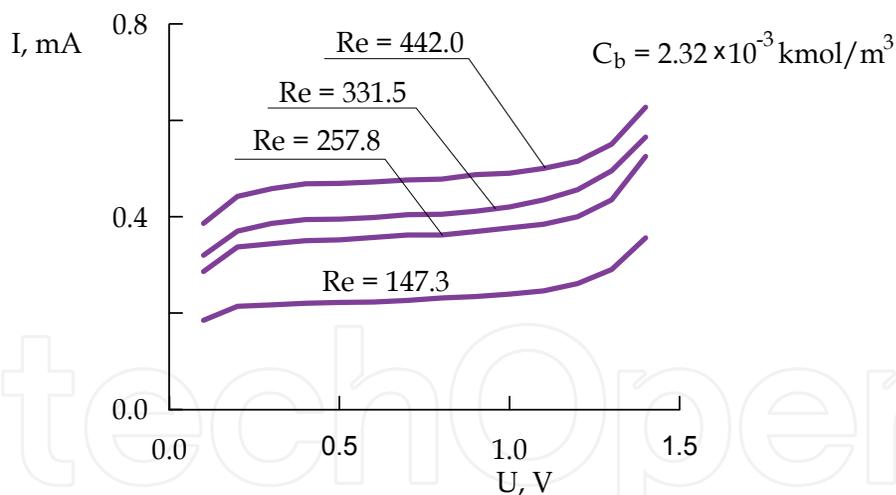


Fig. 8. Examples of the limiting current plateau for the $3/4L$ length cathode

The distribution of the mean mass transfer coefficient along the length of the channel for different Reynolds numbers is shown in Fig. 9.

The measurements obtained were compared with values given by the extension of the Graetz-Leveque solution for mass transfer (Acosta et al., 1985) which are given by

$$\text{Sh} = 1.85(\text{ReSc})^{1/3} \left(\frac{d_h}{x} \right)^{1/3}, \quad (22)$$

where: x - distance from the mass transfer leading edge.

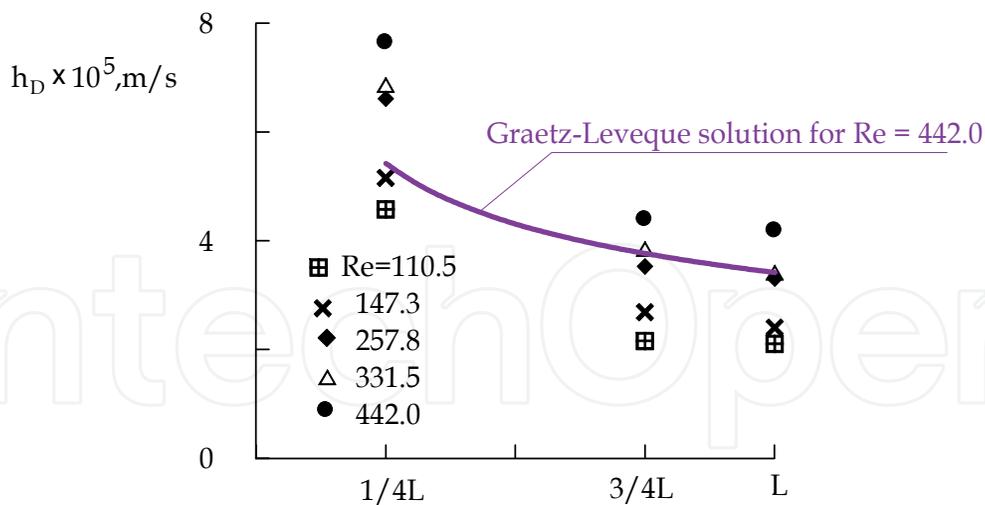
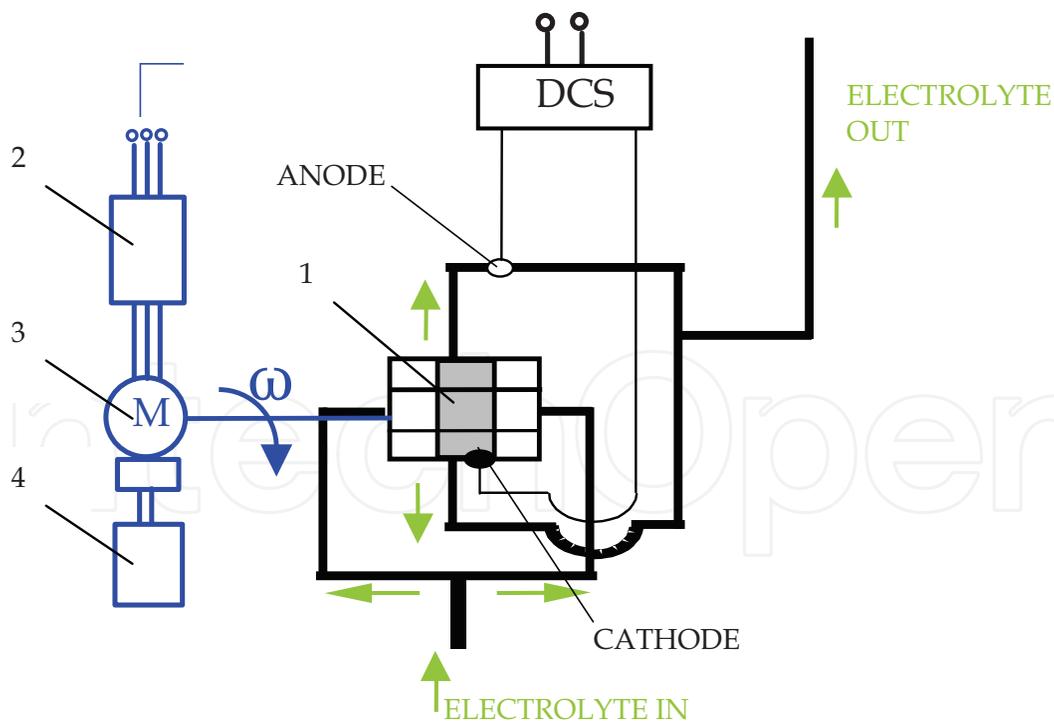


Fig. 9. Variation of mean mass transfer coefficient with the length of the minichannel

5.2 Rotary conditions

Experimental investigations of the mass transfer coefficients in the rotating minichannels were performed using the rig shown in Fig. 4. Additionally, the drive system of the tested ring was applied. The rotor was driven by a three-phase electric motor. The rotational speed was controlled by a speed indicator. A simplified scheme of part of the experimental rig with the ring drive system is shown in Fig. 10.



1 - test section with the ring with minichannels, 2 - inverter, 3 - driving motor, 4 - angular rate sensor.

Fig. 10. Scheme of the rotary part of the rig.

The rotational speed \dot{n} of the minichannels was obtained based on an assumed value 0.1 of the Rossby number. The value of \dot{n} was calculated from the formula:

$$\dot{n} = \frac{\nu Re Ro}{2\pi d^2}. \quad (23)$$

The values of the rotational speed of the ring with minichannels varied between 100 and 534 revolutions per minute.

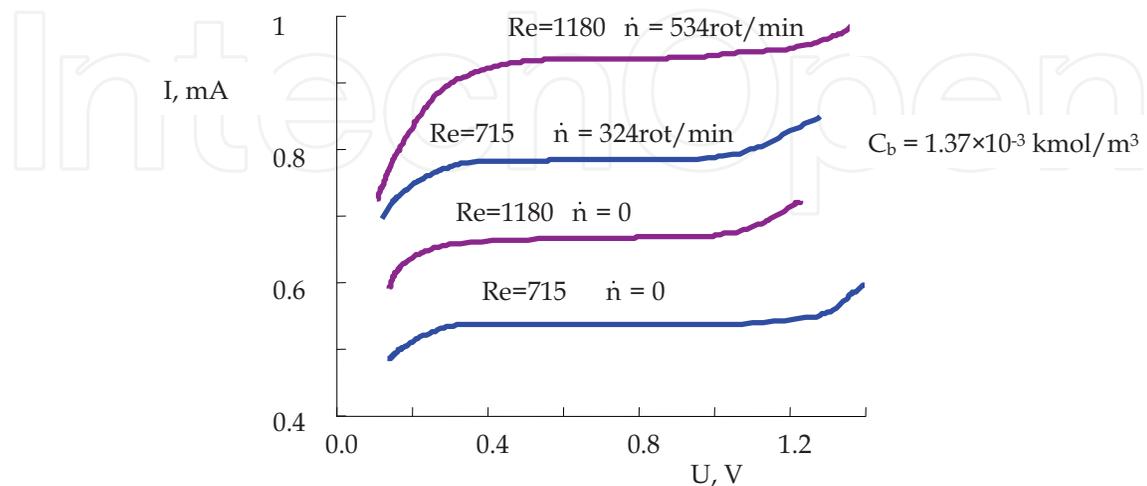


Fig. 11. Influence of the rotation on the limiting current.

Rotation caused intensification of the mass transfer process in the minichannel. The limiting current increased with the increase in the minichannel rotational speed. Examples of the voltammograms are shown in Fig. 11.

Finally from the measurements the dimensionless mass transfer coefficients (Sherwood numbers) were calculated. The results are shown in Fig. 12, where the Rossby number (rotation number) occurs as a parameter.

Based on Eqs (9) and (11) the results were obtained in the forms:

$$j_M = 0.31 Re^{-0.48} \quad (24)$$

for $Ro = 0$, and

$$j_M = 1.93 Re^{0.67} \quad (25)$$

for $Ro = 0.1$.

The electrochemical results were compared with the correlations described by Bieniasz (Bieniasz, 2010) for rotating short curved minichannels of cross-section varying in shape and surface area along the axis, namely

$$j_M = 0.282 Re^{-0.437} + 2.48 Re^{-0.732} Ro \quad (26)$$

and

$$j_M = 0.351 Re^{-0.418} + 2.20 Re^{-0.703} Ro. \quad (27)$$

Bieniasz gave two correlations (26) and (27) depending on the kind of baffle applied in the test section (Bieniasz, 2010). The comparison is shown in Fig. 13.

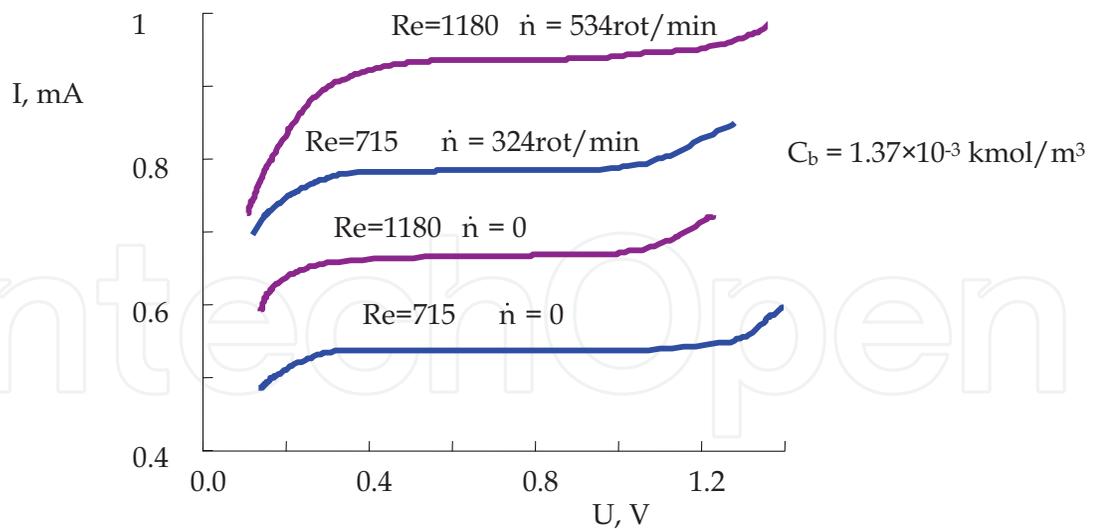
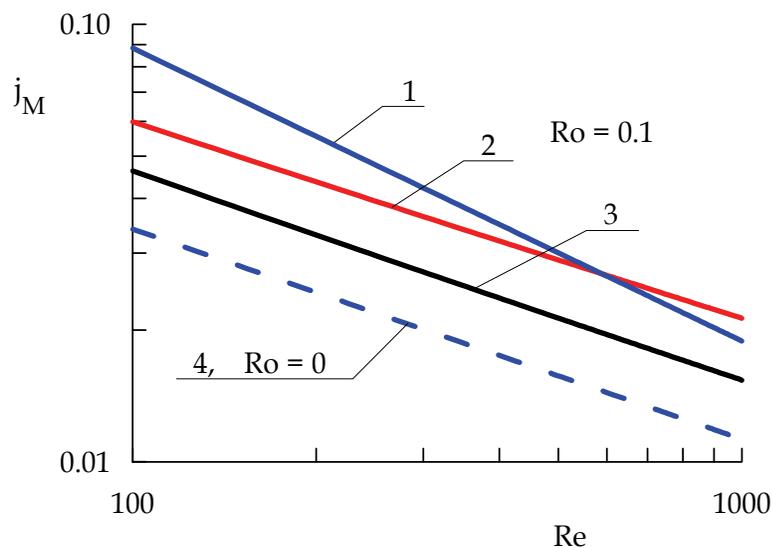


Fig. 12. Influence of rotation on the mass transfer in the circular short minichannel.



1 - circular minichannels, $d = 1.5\text{mm}$, Eq.(25), 2 - curved minichannels, $d_h = 2.36\text{mm}$, Eq.(27), 3 - as previously, Eq.(26), 4 - circular minichannels, $d = 1\text{mm}$, stationary conditions, Eq.(24).

Fig. 13. Chilton-Colburn mass transfer coefficients in short rotating minichannels,

6. Experimental uncertainties of the major parameters

The average relative uncertainties of the complex quantities $y = y(x_1, x_2, \dots, x_i)$ were calculated according to the general relation:

$$\frac{\Delta y}{y} = \left[\frac{\sum_{i=1}^n \left(\frac{\partial y}{\partial x_i} \Delta x_i \right)^2}{y^2} \right]^{\frac{1}{2}} \tag{28}$$

where: Δx_i - the mean uncertainties of the partial measurements

Based on Eqs (19) and (28) the relative uncertainty of the mass transfer coefficient measurement is given by

$$\left| \frac{\Delta h_D}{h_D} \right| = \left[\left(\frac{\Delta I_p}{I_p} \right)^2 + \left(\frac{\Delta A}{A} \right)^2 + \left(\frac{\Delta C_b}{C_b} \right)^2 \right]^{1/2}. \quad (29)$$

The limiting current I_p measurement was made by means of a digital millivoltmeter, so $\left| \frac{\Delta I_p}{I_p} \right| = 0.1\%$ is the uncertainty resulting from the degree of accuracy of the measuring instrument (measurement of the voltage drop at standard resistance).

The average uncertainty in the determination of the cathode surface area $\left| \frac{\Delta A}{A} \right|$ was related to the minichannel inner diameter and length measurements. It was estimated to be 3.4%.

For iodometric titration the following data was necessary in order to obtain $\left| \frac{\Delta C_b}{C_b} \right|$: solution normality of $\text{Na}_2\text{S}_2\text{O}_3$ $N = 1 \pm 0.002$, volume of electrolyte sample $V = (25 \pm 0.1)$ ml and uncertainty of titrant added volume measurement $\Delta V_t = 0.005$ ml. Based on this data the value of $\left| \frac{\Delta C_b}{C_b} \right|$ was calculated as 1.4%.

The relative uncertainty of the mass transfer coefficient measurement was calculated according to Eq.(25) and was 3.7%.

7. Convective heat transfer in circular minichannels

On the basis of the mass transfer coefficient measurements and mass/heat transfer analogy described in section 2, some correlations describing the convective heat transfer in stationary and rotating circular minichannels were obtained.

The equation:

$$\text{Nu} = 0.257\text{Re}^{0.52} \quad (30)$$

describes the dependence of the mean Nusselt number vs Reynolds number for stationary conditions in the Reynolds number range 250 to 1200.

The similar correlation

$$\text{Nu} = 1.714\text{Re}^{0.33} \quad (31)$$

concerns the convective heat transfer in a rotating minichannel. The range of Reynolds numbers was the same as in Eq.(30). Eq.(31) is valid for the Rossby number 0.1.

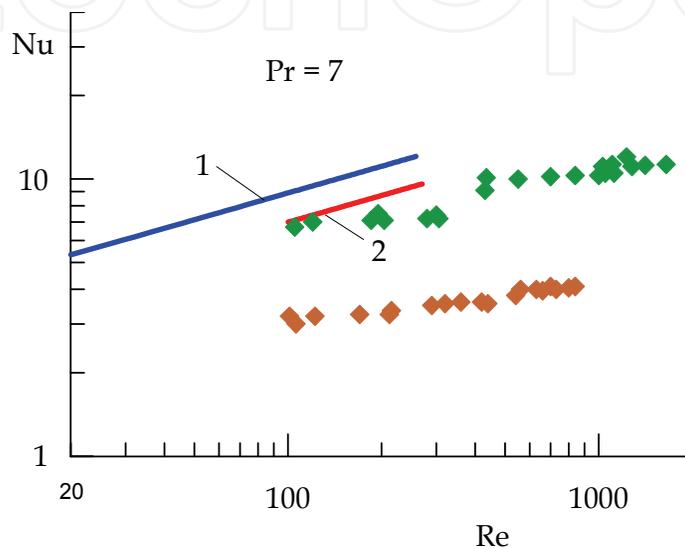
A different correlation was obtained for stationary conditions where convective heat transfer in a short circular minichannel takes place at low Reynolds numbers. It was

$$\text{Nu} = 1.067e^{0.52}\text{Pr}^{1/3}. \quad (32)$$

Correlation (32) is valid for $d/L = 0.1$ and for Reynolds numbers ranging from 20 to 250. The extension of Eq.(32) by the term $(d/L)^r$ and the assumption of the power $r = 1/3$ lead to the following form of Eq.(32):

$$Nu = 2.3Re^{0.52} \left(Pr \frac{d}{L} \right)^{1/3} . \tag{33}$$

Relationship (32) in comparison with the thermal balance results (Celata et al., 2006) is shown in Fig. 14.



1 - heat/mass transfer analogy results, mean Nu number, $d/L = 0.1$; 2 - graphical presentation of the Eq.(33), $d/L = 0.048$; $\blacklozenge\blacklozenge$ experimental thermal balance results, local Nusselt number, $d/L = 0.048$ (Celata et al., 2006); $\blacklozenge\blacklozenge$ as previously, $d/L = 0.016$ (Celata et al., 2006)

Fig. 14. Heat/mass transfer analogy results for a short minichannel in comparison with the thermal balance results.

8. Summary

In this chapter the possibility of applying the mass/heat transfer analogy to the investigation of convective laminar heat transfer in rotating and stationary short minichannels was explored. The author has provided a general form of the mass/heat transfer analogy, assumptions of the processes, as well as the dimensionless numbers and equations describing the analogy. The limiting current method used for mass transfer coefficient determination was described. Some limiting current voltammograms which formed the basis for mass transfer coefficient calculations were provided. The use of an electrochemical technique and the Chilton-Colburn analogy produced correlations describing heat transfer processes in short minichannels.

Results of the mass transfer coefficient uncertainty calculations were also presented.

An important problem in the application of the mass/heat transfer analogy is determination of the analogy uncertainty. In order to estimate the uncertainty of the heat transfer coefficient resulting from application of the mass/heat transfer analogy, a comparison of experimental heat tests, mass transfer experiments and theoretical analysis in defined cases

should be performed. This problem was described in papers by (Wilk, 2004) and (Lucas & Davies, 1970). Taking into account all the facts discussed in these works, one may tentatively conclude that the mass/heat transfer analogy uncertainty is of the same order of magnitude as the uncertainty of the heat transfer coefficient determined by means of a specific measuring technique.

9. References

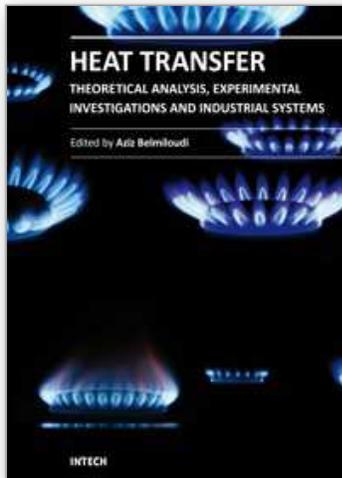
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Over the past few decades there has been a prolific increase in research and development in area of heat transfer, heat exchangers and their associated technologies. This book is a collection of current research in the above mentioned areas and discusses experimental, theoretical and calculation approaches and industrial utilizations with modern ideas and methods to study heat transfer for single and multiphase systems. The topics considered include various basic concepts of heat transfer, the fundamental modes of heat transfer (namely conduction, convection and radiation), thermophysical properties, condensation, boiling, freezing, innovative experiments, measurement analysis, theoretical models and simulations, with many real-world problems and important modern applications. The book is divided in four sections : "Heat Transfer in Micro Systems", "Boiling, Freezing and Condensation Heat Transfer", "Heat Transfer and its Assessment", "Heat Transfer Calculations", and each section discusses a wide variety of techniques, methods and applications in accordance with the subjects. The combination of theoretical and experimental investigations with many important practical applications of current interest will make this book of interest to researchers, scientists, engineers and graduate students, who make use of experimental and theoretical investigations, assessment and enhancement techniques in this multidisciplinary field as well as to researchers in mathematical modelling, computer simulations and information sciences, who make use of experimental and theoretical investigations as a means of critical assessment of models and results derived from advanced numerical simulations and improvement of the developed models and numerical methods.

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