Preliminary research on mass/heat transfer in mini heat exchanger

Joanna Wilk[1*], *Sebastian* Grosicki[1], and *Krzysztof* Kiedrzyński[1]

[1]Thermodynamics Department, the Faculty of Mechanical Engineering and Aeronautics, Rzeszów University of Technology, al. Powstańców Warszawy 12, 35-959 Rzeszów, Poland

Abstract. In the paper the authors present the facility for model investigations of heat/mass transfer in the exchanger characterised by small dimensions. Determination of heat transfer coefficients is an important issue in the design of mini heat exchangers. The built facility enables measurements of mass transfer coefficients with the use of limiting current technique. The coefficients received from the experiment are converted into heat transfer coefficients basing on the analogy between mass and heat transfer. The exchanger considered consists of nine parallel minichannels with a square cross-section of 2mm. In real conditions during the laminar flow through the minichannels the convective heat transfer occurs. Analogous conditions are maintained during the model mass transfer experiment. The paper presents the experimental facility and the preliminary results of measurements in the form of voltammograms. The voltammograms show the limiting currents being the base of mass transfer coefficient calculations.

1 Introduction

Heat transfer in miniscale is an important subject of study in science and technology. Understanding the phenomena occurring in miniscale is essential for designing devices with small dimensions. To explore heat transfer and fluid flow in minichannels many factors should be taken into account. Determination of heat transfer coefficients is the base of the research and design of the mini heat exchangers. In practice, measurements of heat transfer coefficients are made using the thermal balance method. However, in some cases heat transfer experiments can be difficult to carry out. In the case of minichannels the surface and fluid temperature measurements present the significant problem due to small size of the channel. Thermal measurements in minichannels are often difficult because of the small dimensions of the channel which often makes it impossible to measure the basic thermal parameters such as temperature or heat flux. Mass transfer methods can be used as alternative techniques, heat transfer coefficients then are being calculated from a mass/heat transfer analogy. Mass transfer experiments are widely applied to determine heat transfer coefficients on the basis of empirical correlations for mass transfer.

In the paper the authors present the facility for model investigations of heat/mass transfer in the exchanger characterised by small dimensions. The facility enables measurements of mass transfer coefficients with the use of limiting current technique. The heat exchanger examined consists of the parallel minichannels with a square cross-section.

Some authors have used the limiting current technique in the research on mass transfer in minichannels. Papers [1-4] deal with the investigation of mass transfer in circular micro- and minichannels. In [1] and [5, 6] the authors present the results of mass transfer measurements in minichannels of high-speed heat regenerator under rotation conditions. In turn the works [7, 8] contain investigation of rectangular minichannels using the limiting current technique. The paper [9] presents the applicability of the limiting current technique for the research on mass/heat transfer in minichannels and provides an overview of results of mass transfer measurements. The present work and the planned further research may be the supplement to the current available results on mass/heat transfer in minichannels.

2 Research method

2.1 Limiting current technique

The limiting current technique is well known method used in mass transfer investigations. Some researchers use this technique in their study on mass/heat transfer. In addition to the papers presented above the following latest works on mass/heat transfer in nanofluids can also be cited: [10-15].
Limiting current technique involves observing controlled ion diffusion at one of the electrodes, usually the cathode. Once an external voltage is applied to the electrodes which are immersed in the electrolyte, anionic reduction occurs at the cathode and oxidation at the

---

[*] Corresponding author: joanwilk@prz.edu.pl

anode. As a result, electric current arises in the external circuit. The current is proportional to the number of ions reacting at the electrode per unit time. According to Faraday's law, the magnitude, I, of the current generated is given by

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

where: n – number of electrons consumed in electrode reaction, F - Faraday constant, F=96493×10^3 As/kmol, A - surface area of the cathode, N - molar flux density.

If only the diffusion process of ion transport is taken into account, according to Fick's law and the Nernst model (linear dependence of ion concentration vs the distance from the electrode surface in the diffusion layer) [16], one may write

$$I=nFAh_\mathrm{D}(C_b-C_w) \tag{2}$$

where: h_D - mass transfer coefficient, C_b, C_w – the bulk and at the wall ion concentration respectively.

If the anode surface is much bigger than the cathode surface, a further increase in the applied voltage will not lead to increasing of current intensity. The limiting current occurs. 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

$$h_\mathrm{D}=I_p/(nFAC_b). \tag{3}$$

2.2 Principle of mass/heat transfer analogy

There exists an analogy between mass and heat transfer processes. In mass transfer by means of diffusion a fundamental role is played by the gradient of the concentration of the molecules or ions exchanged, whereas in heat transfer it is the gradient of the fluid temperature. Similar terminology and mathematical models are used to describe both exchange processes. Heat transfer results may be converted from those of mass transfer under equivalent experimental conditions. It arises from the similarity of the equations governing the mass and heat transport processes. Sherwood and Nusselt numbers are analogous dimensionless numbers which represent mass and heat transfer intensity. Results of the experiments on mass transfer during the flow through the channel are expressed in the well-known empirical equation

$$\mathrm{Sh}=C\cdot\mathrm{Re}^p\mathrm{Sc}^q \tag{4}$$

where: Re – Reynolds number, Sc– Schmidt number, Sh– Sherwood number, C, p, q – empirical constants.

According to the analogy of mass and heat transfer processes the results for heat transfer can be expressed in the form

$$\mathrm{Nu}=C\cdot\mathrm{Re}^p\mathrm{Pr}^q \tag{5}$$

where: Nu – Nusselt number, Pr– Prandtl number. Dimensionless numbers are given by

$$\mathrm{Nu}=h\cdot d_H/k \quad , \quad \mathrm{Sh}=h_D\cdot d_H/D, \tag{6}$$

$$\mathrm{Pr}=\nu/a, \qquad \mathrm{Sc}=\nu/D, \tag{7}$$

$$\text{and} \quad \mathrm{Re}=w\cdot d_H/\nu, \tag{8}$$

where: h – heat transfer coefficient, d_H – hydraulic diameter of the minichannel, k – thermal conductivity, a – thermal diffusivity, D – diffusion coefficient, ν – kinematic viscosity, w – mean fluid velocity.

It is difficult to fulfil all the mass and heat transfer analogy conditions. The requirement of fluid properties similarity expressed by equal Schmidt and Prandtl numbers is especially difficult to meet. If Sc and Pr are not equal, the ratio of equations (5) to (4) indicates that the results of the mass transfer experiment may be converted to the corresponding heat transfer formula

$$\mathrm{Nu/Sh}=(\mathrm{Pr/Sc})^q \tag{9}$$

The exponent q is the constant determined from empirical investigations. Basing on the available data, the analogy proposed by Chilton and Colburn [17] seems to be most useful when applied in internal flow through minichannels. In the Chilton-Colburn relation the value of the exponent q was found to be 1/3.

2.3 Electrochemical system

A classical system for measurements using the limiting current technique is the reduction of ferricyanide ions at the cathode and oxidation of ferrocyanide ions at the anode. A solution of $NaOH$ or KOH is used as the background electrolyte. The oxidation-reduction process under convective-diffusion controlled conditions is written as:

$$Fe(CN)_6^{-4} \leftrightarrow Fe(CN)_6^{-3}+e, \tag{10}$$

in this case n=1.

In the present work an aqueous solution of equimolar (0.01 molar) quantities of $K_3Fe(CN)_6$ and $K_4Fe(CN)_6$ and molar solution of $NaOH$ as the background electrolyte were used. Electrodes applied have been made from nickel. To achieve the process under diffusion controlled conditions written by eq.(10) the removing of oxygen from the electrolyte is required. In the present study oxygen was removed by washing the electrolyte with nitrogen.

3 Experimental investigations

3.1 Research stand

Mass transfer measurements were performed on the research stand built specifically for the mini heat exchanger investigations. The general scheme of the measuring stand is shown in Fig. 1. Elements of the facility which had contact with the electrolyte were made of chemically resistant materials. Oxygen was released from the electrolyte by nitrogen bubbling. Because the decomposition in concentration of the reacting ions occurs under sunlight [18] the electrolyte had no contact with sunlight within the whole measuring system. The anode bigger than cathode was located behind the cathode (see Fig. 1) in the direction of the electrolyte flow. Test section used for the electrochemical experiment is shown in Fig. 2.

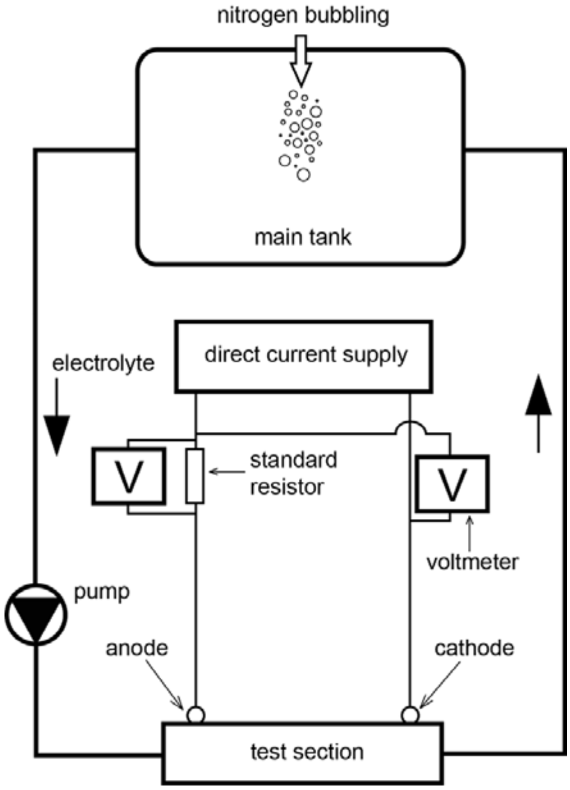

Fig. 1. Scheme of the experimental facility.

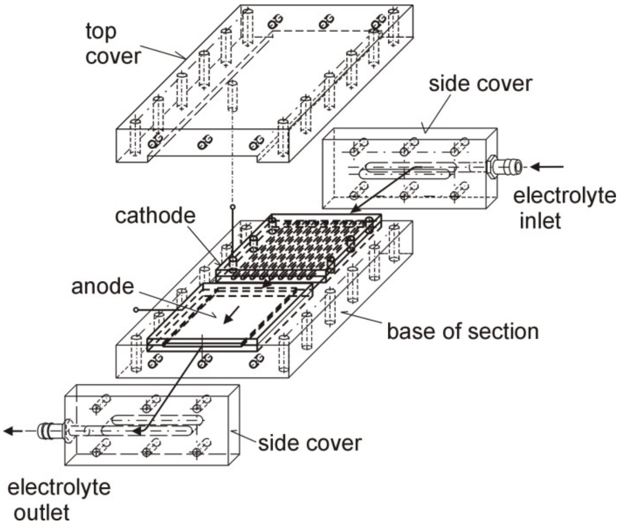

Fig. 2. Test section.

The part of test section was the model of the mini heat exchanger considered. Made from nickel the model of the exchanger consisted of nine parallel minichannels with a square cross-section of 2 mm. The inner surface of the minichannels worked as the cathode in the electrochemical experiment. Thus, the cathode surface was modelling the heat transfer surface in real conditions. Fig. 3 presents the geometry of the mini heat exchanger tested. Dimensions are given in mm.

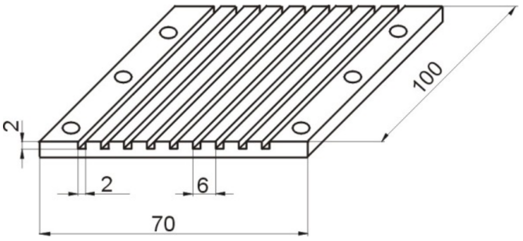

Fig. 3. Geometry of the mini heat exchanger.

Before the experiment the surfaces of electrodes were specially prepared. They were polished with the use of greasy diamond abrasive compound. The electrode polishing has reduced the surface roughness and the same the most suitable measurements has been achieved [18].

3.2. Measurement procedure

The base parameter measured on the research stand was the limiting current representing controlled ion diffusion at the cathode. The increasing of the applied voltage induced the increase in current until reaching the I_p. Current parameters were controlled and measured using voltmeters, direct current supply and standard 1 Ω resistor.

Temperature conditions of the experiment were regulated using the air conditioning system. In this way, the temperature was maintained at 22°C. Constant temperature of the electrolyte allowed the determination of temperature dependent thermophysical properties of the electrolyte: density ρ, dynamic viscosity μ and diffusion coefficient D. The properties have been calculated according to the formulas [19, 20]

$$\rho=1137{,}9-0{,}33T \tag{11}$$

$$\mu=1{,}12\cdot 10^{-6}\exp(2056{,}8T^{-1}) \tag{12}$$

$$D=1{,}772\cdot 10^{-6}\exp(-2348{,}9T^{-1}) \tag{13}$$

where T is the electrolyte temperature in K.

Values of the electrolyte density, dynamic viscosity and diffusion coefficient are summarized in Table 1.

Table 1. Electrolyte properties at 22°C.

ρ, kg/m^3	μ, N·s/m^2	D, m^2/s	C_b, kmol/m^3
1039,65	$1194{,}56\cdot 10^{-6}$	$6{,}17\cdot 10^{-10}$	$29{,}96\cdot 10^{-4}$

Before the experimental investigations the ion concentration has been measured. Iodometric titration technique has been used [15]. Because of minichannels of the exchanger examined are characterized by a large ratio L/d_H (where L is a channel length), the decrease of ion concentration in axial direction may occur.

According to the scheme presented in Fig.4 the difference between the ion concentration at the electrolyte inlet C_{in} and at outlet C_{out} exists. Basing on the balance of the electrolyte molar flux [9] and taking into account eq.(3) the ion concentration at the minichannel outlet is given by

$$C_{out} = C_{in} - I_p/(nF\dot{V}), \tag{14}$$

where $\dot{V}$ is the electrolyte volumetric flow.

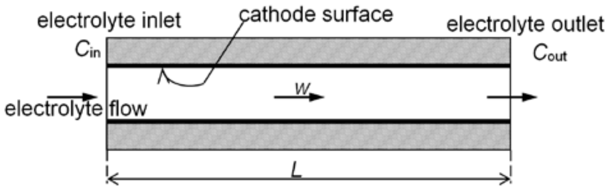

Fig. 4. Electrolyte flow through a long minichannel.

The value of C_{in} was measured by iodometric titration and the bulk ion concentration C_b necessary for mass transfer coefficients calculations was calculated from

$$C_b = \frac{C_{in} - C_{out}}{\ln(C_{in}/C_{out})}. \tag{15}$$

The obtained value of C_b is in Table 1.

The next parameter necessary for development of the research results was the volumetric flow of the electrolyte $\dot{V}$. Values of $\dot{V}$ were determined for five configurations of the pump. The volumetric method has been applied. The flow time of a given electrolyte volume has been measured. On the basis of $\dot{V}$ the mean velocity of the electrolyte flowing through the minichannels of the exchanger has been obtained.

4 Results and discussion

4.1. Measurement results

As a primary results of the measurements plots of the current passing through the cathode against applied voltage have been obtained. The plots named voltammograms are shown in Fig. 5.

As can be seen in Fig. 5 the voltammograms are characterised by the appearance of a flattened section in the curve. It represents the limiting current value. The most representative flat section is in the case of the lowest electrolyte velocity. Reynolds number for this case is about 1430 which indicates a laminar flow. In other cases, there is a transitional and turbulent flow what may be the reason for shortening the flat section of voltammograms representing limiting current.

Mean mass transfer coefficient at the inner surface of the square minichannel of the exchanger has been calculated for laminar flow conditions. The parameters received: mean velocity of the electrolyte, inner surface of minichannels – cathode surface, limiting current and mass transfer coefficient are summarised in Table 2.

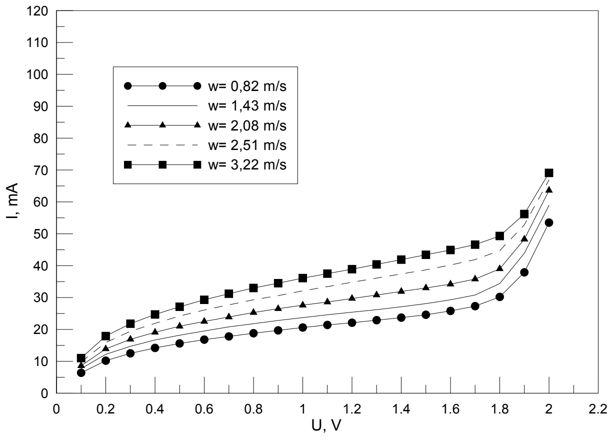

Fig. 5. Voltammograms for the reduction of ferricyanide ions at the cathode being the inner surface of the nine square minichannels of the exchanger.

Table 2. Results of measurements of basic parameters

***w*, m/s**	***A*, m^2**	**I_p, A**	**h_D, m/s**
0,82	$7{,}2\cdot10^{-3}$	$23\cdot10^{-3}$	$11{,}05\cdot10^{-6}$

The average relative uncertainty of mass transfer coefficient measurements with the use of limiting current technique is given by

$$\frac{\Delta h_D}{h_D} = \left(\left(\frac{\Delta I_p}{I_p}\right)^2 + \left(\frac{\Delta A}{A}\right)^2 + \left(\frac{\Delta C_b}{C_b}\right)^2\right)^{1/2} \tag{16}$$

where: ΔI_p, ΔA, ΔC_b – are the mean uncertainties of the partial measurements of limiting current, cathode surface and ion concentration, respectively. Basing on the previous investigations of circular minichannels [2, 3, 15] the $\Delta h_D/h_D$ value was estimated to be about 2,5%.

4.2 Mass/heat transfer analogy results

In order to preliminary validation of the results received calculations based on the analogy between mass and heat transfer have been performed. In the first step dimensionless numbers for mass transfer have been calculated. Next, Chilton-Colburn analogy in the form of eq.(6) has been applied. Prandtl number equal 3,25 was adopted for calculations. Values of dimensionless numbers are included in Table 3.

Table 3. Dimensionless numbers for mass and heat transfer during the laminar flow through the square minichannel.

Re	**Sh**	**Sc**	**Nu**	**Pr**
1430	35,82	1862,24	4,31	3,25

Dirichlet boundary condition of constant temperature at the wall for heat transfer corresponds to the situation of constant concentration at the wall for mass transfer. The mass transfer investigations carried out by limiting current technique are characterised by constant ion concentration at the cathode. Thus, the analogical condition of constant temperature is correct. The literature data about fully developed laminar flow in square channels give the Nusselt number to be 2.98 [21] under a constant wall temperature boundary condition. In turn the another conventional correlation from the literature [22] for the prediction of Nusselt number during the fully developed laminar flow through the rectangular duct give Nu to be 3,55 in the case of square channel. As a most of the literature data on heat transfer in minichannels give the results of an enhancement in heat transfer in comparison to conventional channels, the results obtained in current study may be considered correct.

5 Conclusions

Preliminary experimental investigations on mass/heat transfer in square minichannels of the model of mini heat exchanger have allowed to formulate some conclusions from the obtained results.

Under laminar flow conditions the voltammograms received were characterised by the longer and more pronounced flat section representing the limiting current than in transitional and turbulent regime. Thus, more accurate results of mass transfer measurements with the use of limiting current technique can be expected under laminar flow conditions.

As the channel considered was characterized by the high value of L/d_H, changes of ion concentration along the channel length were occurred. Therefore, it is important to take into account the mean value of concentration in the calculation of mass transfer coefficient.

The use of the analogy of mass and heat transfer gave a higher values of heat transfer coefficient than those in conventional channels. However, further research for obtaining mass/heat transfer processes in square minichannels of a model heat exchanger are necessary.

References

1. J. Wilk, Int. J. of Heat and Mass Transfer **47**, 1979-1988 (2004)
2. J. Wilk, Exp. Thermal and Fluid Sci. **33**, 267-272 (2009)
3. J. Wilk, Exp. Thermal and Fluid Sci. **38**, 107-114 (2012)
4. O. N. Sara, O. B. Ergu, M. E. Arzutug, S. Yapici, Int. J. of Thermal Sci. **48**, 1894-1900 (2009)
5. B. Bieniasz, Int. J. of Heat and Mass Transfer **53**, 3166-3174 (2010)
6. B. Bieniasz, Heat Mass Transfer **50**, 1211-1223 (2014)
7. R. E. Acosta, R. H. Muller, C. W. Tobias, AIChE J. **31**, 473-482 (1985)
8. O. B. Ergu, O. N. Sara, S. Yapici, M. E. Arzutug, Int. Commun. Heat Mass Transfer **36**, 618-623 (2009)
9. J. Wilk, Exp. Thermal and Fluid Sci. **57**, 242-249 (2014)
10. H. Beiki, M. N. Esfahany, N. Etesami, Microfluid Nanofluid **15**, 501-508 (2013)
11. H. Beiki, M. N. Esfahany, N. Etesami, Int. J. of Thermal Sci. **64**, 251-256 (2013)
12. N. Keshishian, M. N. Esfahany, N. Etesami, Int. Commun. Heat Mass Transfer **46**, 148-153 (2013)
13. C. Liu, H. Lee, Y. H. Chang, S. P. Feng, J. Colloid Interface Sci. **469**, 17-24 (2016)
14. J. Wilk, S. Grosicki, J. of Physics **745,** 032084 (2016)
15. J. Wilk, S. Grosicki, Int. J. of Thermal Sci. **129**, 280-289 (2018)
16. A. J. Bard, L. R. Faulkner, *Electrochemical methods* (John Wiley & Sons 2005)
17. T. H. Chilton, A. P. Colburn, Ind. And Engineering Chemistry **26**, 1183-1187 (1934)
18. D. A. Szanto, S. Cleghorn, C. Ponce-de-Leon, F. C. Walsh, AIChE J. **54**, 802-810 (2008)
19. M. Hopkowicz, Z. Pietrzyk, Inż. Chem. **4**, 843-853 (1977)
20. B. Bieniasz, J. Wilk, Int. J. of Heat and Mass Transfer **38**, 1823-1830 (1995)
21. S. G. Kandlikar, S. Garimella, D. Li, S. Colin, M. R. King, *Heat transfer and fluid flow in minichannels and microchannels*, (Elsevier Ltd. 2006)
22. P.-S. Lee, S. V. Garimella, D. Liu, Int. J. of Heat and Mass Transfer **48**, 1688-1704 (2005)