International Journal of Thermal Sciences 48 (2009) 1894–1900

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Experimental study of laminar forced convective mass transfer and pressure drop in microtubes

O.N. Sara*, Ö. Barlay Ergu, M.E. Arzutug, S. Yapıcı

Department of Chemical Engineering, Faculty of Engineering, Atatürk University, 25240 Erzurum, Turkey

ARTICLE INFO

Article history:
Received 30 May 2008
Received in revised form
17 January 2009
Accepted 17 January 2009
Available online 19 March 2009

Keywords:
Convective mass transfer
Convective heat transfer
Friction factor
Microtube

ABSTRACT

The investigation of laminar convective mass transfer and friction factor was performed experimentally for the circular tubes with the diameter of 0.20 mm and the L/d values in the range of 100–500 for a Reynolds number range of 40–1400. The pressure drop experiments were conducted with distilled water, and the mass transfer experiments were carried out with an electrochemical solution by using the electrochemical limiting diffusion current technique. The friction factor results showed good agreement with the classical Poiseuille flow theory, while Sherwood numbers are smaller than those obtained by conventional correlations.

© 2009 Elsevier Masson SAS. All rights reserved.

1. Introduction

With the development of microfabrication technology, microfluidic devices (MFD) have been increasingly used in many scientific and industrial applications. Microtubes are one of the essential geometry for MFD, such as microheat exchanger, microreactor, etc. [1–12]. In recent years, a number of researchers have reported the heat transfer and pressure drop data for laminar and turbulent liquid or gas flow in microchannels. Yu et al. [2] experimentally tested the water flow and nitrogen gas flow through the microtubes with the diameters of 19, 52 and 102 μm for Reynolds number from 250 to 20,000 and Pr ranging from 0.7 to 5. They reported that in the turbulent regime the values of Nusselt number were higher than those was predicted by macrotubes' correlations. Adams et al. [3] conducted an experimental work for turbulent region heat transfer of water flow through the tubes with the diameter ranging from 0.76 to 0.109 mm. They found that the experimental Nusselt numbers were higher than those predicted by macrotube heat transfer correlations. They suggested modified Gnielinski correlation in the following form: $Nu = Nu_G[1 + 1.6 \times 10^{-5} Re(1 - (d/D_o)^2)]$, where D_o is 1.164 mm. Celata et al. [4] performed an experimental work to investigate the hydraulic and heat transfer characteristics of R114 in a microtube with the diameter of 0.130 mm for Reynolds numbers in the range of 100–8000. It was claimed that laminar flow to turbulent flow transition occurred at a Reynolds number between 1880 and 2480. Mala and Li [5] measured the pressure drop for the flow of water in the microtubes with the diameters ranging from 50 to 254 μm. Their results showed that the experimental results for large diameter microtubes are in rough agreement with the conventional theory, while for microtubes with smaller diameters there are significant departures from conventional theory. For lower Reynolds numbers the pressure drop is approximately the same as predicted by Poiseuille flow theory, but for higher Reynolds numbers the friction factors are higher than those predicted by the conventional theory. Li et al. [6] studied the flow characteristics of water flow in the microtubes with the diameter of 79.9–116.3 μm, 100.25–2005.3 μm, and 128.76–179.8 μm. The experimental results showed that the flow characteristic of the laminar flow in the microtubes with the diameters larger than 80 μm has no difference from the macrotubes and the transition from laminar to turbulent flow occurred at Reynolds numbers between 1700 and 2000. Owhaib and Palm [7] conducted an experimental work on convective heat transfer with R134a fluid through the circular microchannels with 1.7, 1.2 and 0.8 mm as inner diameters, and Reynolds numbers in the range of 1000–16,000. Their results showed that the classical correlation was in good agreement with the experimental data in the turbulent regime, and the heat transfer coefficients were almost identical for all three diameters for the laminar flow. Morini et al. [8] investigated experimentally

* Corresponding author.
E-mail address: osara@atauni.edu.tr (O.N. Sara).

1290-0729/$ – see front matter © 2009 Elsevier Masson SAS. All rights reserved.
doi:10.1016/j.ijthermalsci.2009.01.021

Nomenclature

A	area [m^2]
c	concentration [mol m^{-3}]
D_i	diffusion coefficient [m^2 s^{-1}]
d	tube diameter [m]
F	Faraday constant
f	friction factor
Gz_H	Graetz number for heat transfer
Gz_M	Graetz number for mass transfer
I_{lim}	limiting current [A]
L	tube length [m]
k	mass transfer coefficient [m s^{-1}]
$\overline{Nu}$	average Nusselt number
Nu	local Nusselt number
ΔP	pressure drop [Pa]
Pr	Prandtl number
Re	Reynolds number ($= du\rho/\mu$)
Sc	Schmidt number
$\overline{Sh}$	average Sherwood number ($= dk/D_i$)
α	thermal diffusivity [m^2 s^{-1}]
u	velocity [m s^{-1}]
ρ	density [kg m^{-3}]
μ	viscosity [kg m^{-1} s^{-1}]

Subscripts

d	developing
e	exit
ex	experimental
i	inlet
LM	logarithmic mean
net	net
o	outlet
pr	predicted
s	surface
t	total

the flow characteristics of nitrogen in the microtubes having nominal inner diameter of 762, 508, 254 and 127 μm. They reported that in laminar regime the Poiseuille law correctly predicts the value of the pressure drop, and the transition laminar to turbulent flow takes place at a Reynolds number between 1800 and 2900.

More recently, Yang and Lin [9] carried out an experimental work to study the forced convective heat transfer of water flowing through the microtubes with the inner diameters ranging from 123 to 962 μm using the liquid crystal thermography temperature measurement. They reported that the conventional heat transfer correlation for laminar and turbulent flow can be well applied for the prediction of heat transfer in microtubes, and the transition occurs at Reynolds number in range of 2300–3000. Detailed reviews of the heat transfer and pressure drop studies in microchannels were given by several researchers [10–15].

Briefly expressing, there are large scatter in the experimental results for flow friction and heat transfer results in microtubes. As has been pointed out by many researchers [10–15] these inconsistencies can be attributed to several factors such as uncertainty in channel size, unperfectness in the defined geometry, relative roughness, compressibility, viscous dissipation effect, property variation with temperature, electrical double layer, axial conduction, inlet/outlet effect and heat loss. The literature review also reveals that in spite of the many work on heat transfer and pressure drop in microtube, the mass transfer studies are very limited. Acosta et al. [16] investigated experimentally the mass and momentum transport in narrow flow gaps with dimension of 0.2–0.5 mm for Reynolds number in the range of 1300–2200. It was found that the existing correlations of much larger hydraulic diameter can be applied for the narrow channel as well. van Male et al. [17] studied both numerically and experimentally, the heat and mass transfer in a square microchannel with asymmetric heating. They reported Nusselt number and Sherwood number correlations for channel heated from topside for the laminar and plug flow. Even though there is analogy between heat transfer and mass transfer, it is not yet clear its applicability to microchannels. Therefore, it is necessary to perform further work on the mass transfer in microchannels to verify mass transfer mechanism in microchannels. This study provides an experimental investigation on the laminar forced convective mass transfer and pressure drop characteristic of the liquid flowing through the microtubes.

2. Experimental set-up and data reduction

The schematic diagram of the experimental set-up is shown in Fig. 1. It consists of a high-pressure nitrogen gas tube, multimeters, a DC power supply, a microfilter, a digital balance, a circulated water bath and test section. The flow to the test section was provided by high-pressure nitrogen gas and the flow rates were adjusted by a two-stage gas regulator. The fluid passes through a microfilter before entering the test section and was collected after the test section to weigh. Two multimeters were used to measure the current and voltage in the system. The temperature of the electrolyte, which is the working liquid, was kept constant at 25 ± 0.1 °C by circulated water bath. The test channels used were circular tubes made of 99, 95% nickel provided from GOODFELLOW, with diameter of 200 μm with different L/d ratio ranging from 100 to 500. The dimensions of the tubes used were given in Table 1. The diameters of the tubes were measured by NİKON MM 400 L video measuring microscope. As shown in Fig. 1b, a nickel tube with diameter of 8 mm was attached as anode after the test channel. The pressure drop in test section was measured by pressure transmitter made by KELLER in range 0–6 bar ± 0.5% FS.

The mass transfer coefficients were determined by using the electrochemical limiting diffusion current technique (ELDCT). The ELDCT has been used in several studies and detailed information can be found in [18,19], therefore, a brief description was given here. This technique is based on diffusion-controlled reaction at electrode surface. The electrolyte used in the mass transfer measurement consisted of 0.005-mol dm^{-3} (M) potassium ferricyanide as cathodic reactant, 0.02 M potassium ferrocyanide as anodic reactant and 0.5 M potassium carbonate as supporting electrolyte. In this study microtubes were used as a cathode and to assure a cathodic controlled-reaction, the anode surface area was chosen approximately 100 times higher than cathode surface area depending on the length of microtubes, and the concentration of ferrocyanide is 4 times higher than that of ferricyanide. The diffusion coefficient of the ferricyanide ion was obtained by using electrochemical rotating disc method [44], and the diffusion coefficient and Schmidt number of the electrolyte were calculated to be 6.85×10^{-10} m^{2}s^{-1} and 1444, respectively. The rate of mass transfer in the present study was characterized by mass transfer coefficient (k) as expressed following:

$$k = \frac{I_{lim}}{nFA\Delta c_{LM}} \quad (1)$$

where I_{lim} is the limiting current, A the inner surface area of the microtube, n number of the transferred electrons in electrochemical

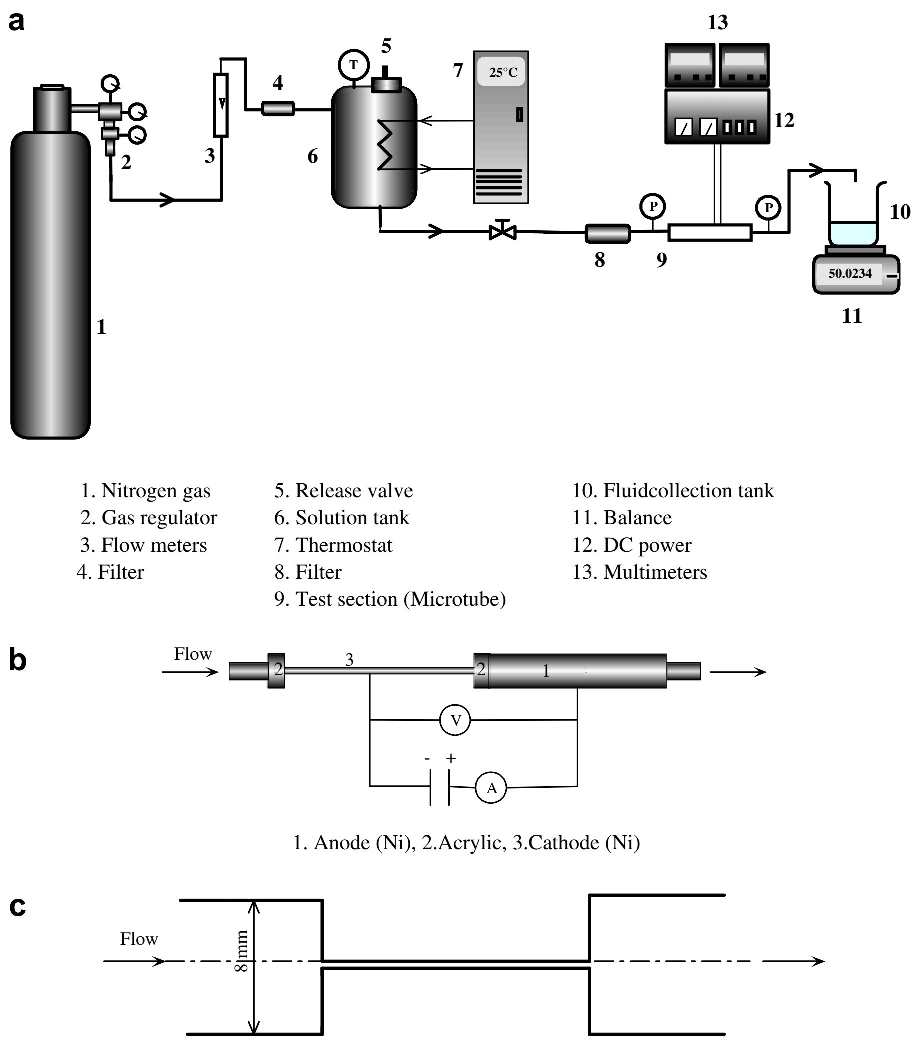

Fig. 1. Experimental set-up.

reaction (=1 for this study), F the Faraday constant and Δc_{LM} the logarithmic concentration difference, which is expressed as

$$\Delta c_{LM} = \frac{(c_i - c_s) - (c_o - c_s)}{\ln((c_i - c_s)/(c_o - c_s))} \tag{2}$$

where c_i, c_o and c_s are the concentrations of active ions in the bulk at inlet and outlet and at the electrode surface, respectively. Under limiting current condition, $c_s = 0$, Eq. (2) reduces to the following equation:

$$\Delta c_{LM} = \frac{c_i - c_o}{\ln(c_i/c_o)} \tag{3}$$

The outlet concentration of ferricyanide, c_o, can be calculated by

$$c_0 = c_i - \left[\frac{4I_{lim}}{nF\pi d^2 u}\right] \tag{4}$$

where d is the diameter of the tube and u the mean velocity.

The measured pressure drop ΔP_t includes the inlet ΔP_i, exit ΔP_e and developing flow ΔP_d, pressure drop contributions, and the net pressure drop, ΔP_{net}, can be calculated by

$$\Delta P_{net} = \Delta P_t - \Delta P_i - \Delta P_e - \Delta P_d \tag{5}$$

where ΔP_i and ΔP_e can be estimated using following relations:

$$\Delta P_i = K_i \frac{\rho u_i^2}{2} \tag{6}$$

$$\Delta P_e = K_e \frac{\rho u_e^2}{2} \tag{7}$$

The values of K_i and K_e for macrochannels can be found from the literature [20], but for microchannels these values show large differences [6,8,21–23]. Several researchers also reported that these values can be found from the methods for macrochannels

Table 1
Dimension of the used tubes.

No.	Length (mm)	Measured nominal diameter (μm)	L/d	Material
A	20.22	205	98.63	Nickel tube
B	30.10	206	146.11	
C	39.84	202	197.22	
D	49.60	200	248.00	
E	69.90	203	344.33	
F	99.94	203	492.31	
G	19.98	332	60.20	Stainless steel tube
H	31.79	332	95.75	

[24,41,45]. In addition, the sections before and after microchannel of the present work, in which the expansion and contraction occurred, are macro in size. Both K_i and K_e were taken equal to 1 from figure derived by Kays and London given in [24] in that case the area of reservoir is much larger than the area of microtube, which is the case for this work. The pressure drop contribution due to developing flow can be determined by using following expression [24], and Kohl et al. [41] claimed that it can be ignored if the ratio L/d is greater than 300.

$$\Delta P_d = K_\infty \frac{\rho u^2}{2} \tag{8}$$

The K_∞ value was taken as 1.553 for trapezoidal microchannel [23] and 1.25 for very long tubes [28]. The K_∞ value was given by Chen [25] in the form of the following equation cited by many researchers for tubes [8,24]:

$$K_\infty = 1.2 + \frac{38}{Re} \tag{9}$$

and in this study K_∞ was calculated by using Eq. (9).

Friction factor was expressed as follows:

$$f = \frac{2\Delta P_{net}}{(L/d)\rho u^2} \tag{10}$$

Finally, the experimental uncertainty was determined using the method described by Holman [26] and the uncertainties of major parameters are presented in Table 2.

3. Results and discussion

3.1. Pressure drop

The pressure drop measurement was performed with distilled water at 25 °C ± 0.1.The detail of the test section used for the pressure drop measurements is shown in Fig. 1(c). The net pressure drops in test section were calculated by using Eq. (5). The hydrodynamic entrance length in laminar flow is expressed by $L_h/d = 0.05Re$ for macrochannels [27]. In this study, the ratios of the length of hydrodynamically developing flow to the whole length of the tube, L_h/L, are in the range of 0.005–0.7 depending on Reynolds number and total tube length. The entrance effect was taken into consideration for all tubes (A–F). Fig. 2 shows the pressure drops versus Reynolds numbers for different tube length (tubes A–F). As seen from Fig. 2, the pressures drops increase with increasing tube length and Re. This behaviour is similar to that in macrochannel flow. According to conventional theory, for the laminar flow in the circular channel at constant fluid property, the relation between the pressure gradient in the form of $\Delta P/L$ and Reynolds number can be expressed as $\Delta P/L = aRe$, where a is a constant depending on tube diameter and fluid property; for this study this constant is found to be 0.00294 in dimension of MPa/m. Fig. 3 gives the plot of the experimental results of $\Delta P/L$ versus Re for tubes A–F. The correlation of experimental data gave the following equation with $r^2 = 0.9608$. It can be seen that the exponent of the Reynolds number is very close to that of conventional channels for Poiseuille flow.

$$(\Delta P/L) = 0.002627Re^{1.021} \tag{11}$$

In Fig. 3, the dotted line shows the values based on conventional theory and solid line those obtained by Eq. (11). As seen from this

Table 2
Experimental uncertainties of the major parameters.

Quantity	Uncertainty	Quantity	Uncertainty
Balance	±0.1 mg	Pressure	±0.5% FS
Tube length	±3–5 µm	Velocity	±3.10%
Tube diameter	±3 µm	Reynolds number	±3.50%
Current	±1.0%	Mass transfer coefficient	±4.90%
Voltage	±0.5%	Sherwood number	±5.38%
Concentration (inlet)	±0.8%	Diffusion coefficient	±1.69%
Concentration (outlet)	±4.5%	Friction factor	±16.33%

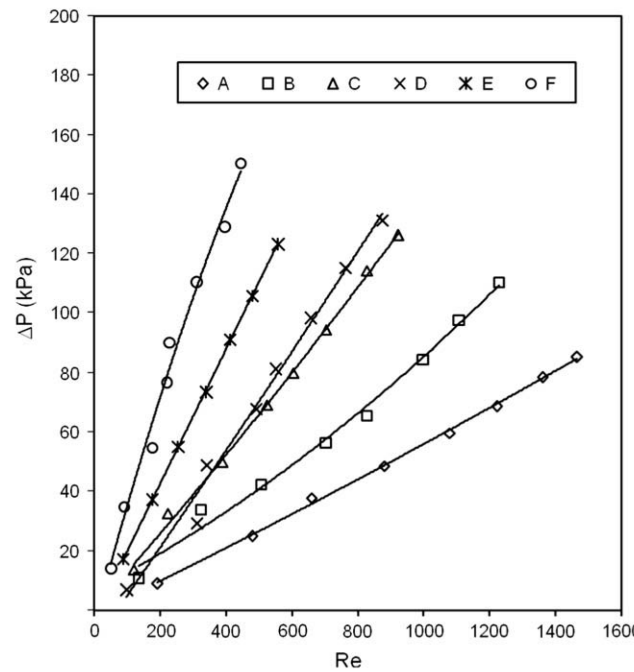

Fig. 2. Variation of pressure drop with Reynolds number.

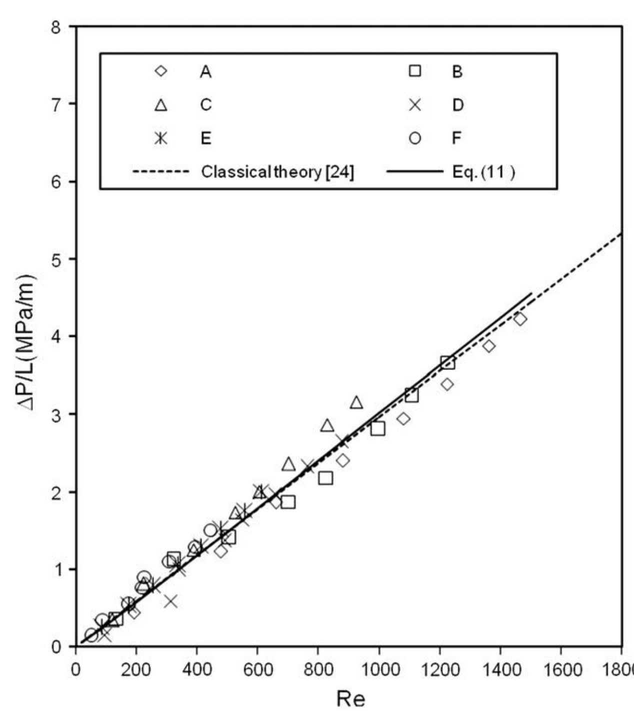

Fig. 3. Variation of $\Delta P/L$ with Reynolds number.

figure, the agreement between the values obtained by Eq. (11) and those by classical theory is very good with an average deviation of 2.24%. The pressure drop values were converted to the friction factors using Eq. (10), and the friction factors were plotted versus *Re* for A–F tubes in Fig. 4. To compare with experimental results given in Fig. 4, the values obtained from 64/*Re* which is valid for Poiseuille flow are also presented in the figure. The figure indicates that the experimental friction factors are in very good agreement with the theoretical values. From the experimental data, it was obtained that average *fRe* is equal to 63.09 ± 2.73. In the studies on the pressure drop in microchannels, generally, the experimental results have been compared with those of conventional channel. Despite some works claim that the experimentally obtained friction factor values in microchannel are smaller or higher than conventional values [10–15], many studies have indicated that the friction factors in microtubes can be adequately predicted by the conventional correlations [9,23,28–30,41]. Some researchers reported an early transformation from laminar to turbulent flow at a Reynolds number in range of 300–1000 [5,31,32,34]. However, in the present work, no transition from laminar to turbulent was observed in the investigated Reynolds number range.

3.2. Mass transfer

Figs. 5 and 6 show the variation of the average mass transfer coefficient with Reynolds number and tube length. As seen from these figures, the average mass transfer coefficients change in range of 3×10^{-6}–2.4×10^{-5} ($\mathrm{m\,s^{-1}}$), increase with increasing Reynolds number, and decrease with increasing tube length. This behaviour is similar to that of macrotube flow. As well known, in laminar channel flow, the mass/heat transfer coefficient decreases with axial direction from tube inlet to downstream of the pipe, and at fully developed conditions it reaches at a certain constant value. For laminar flow in macrotube, the thermal entrance length is defined as $L_{th} = 0.05 Re\, Pr\, d$ [27], and a modified form of this equation can be used for mass transfer using *Sc* instead of *Pr* [27]. When for the present study the modified equation is used, the mass entrance

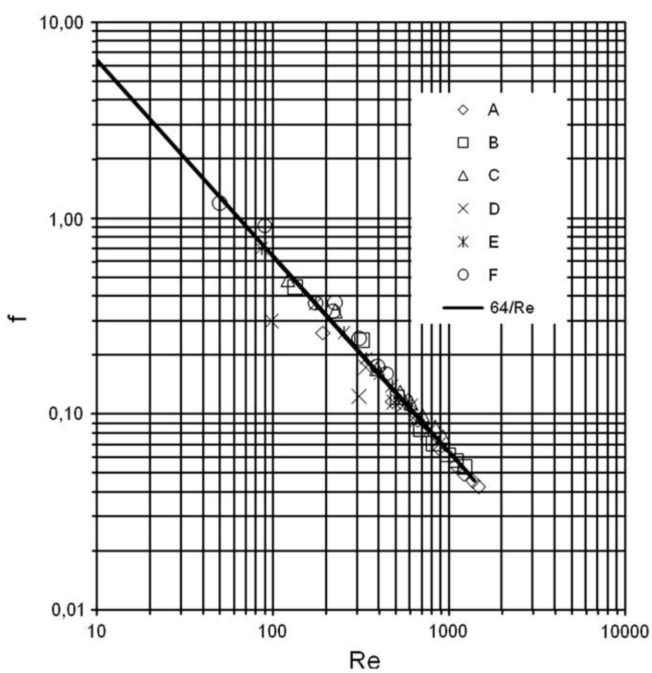

Fig. 4. Variation of *f* with Reynolds number.

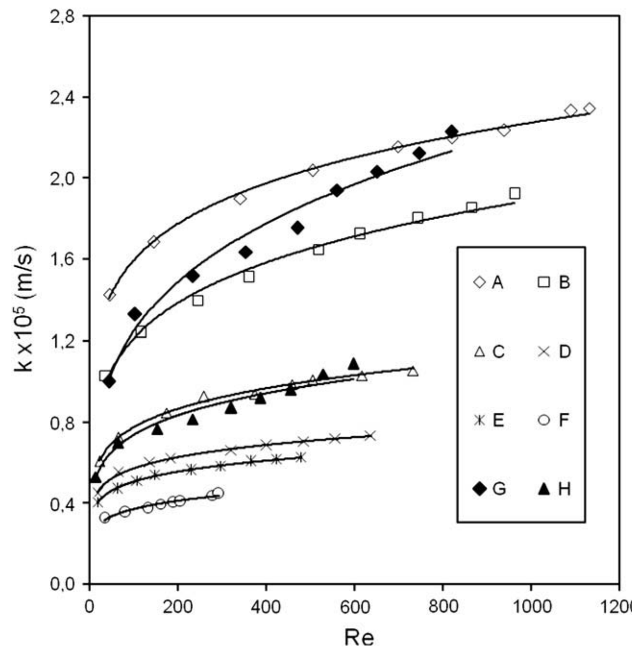

Fig. 5. Variation of mass transfer coefficients with Reynolds number.

length was found to be in the range of 300–1500 mm depending upon *Re*; therefore, experimentally measured mass transfer coefficients are for developing mass transfer boundary layer. The hydrodynamic entrance lengths for the present work have a value between 2% and 60% of the whole tube length depending upon tube length, diameter and *Re*. For mass transfer, a fully developed concentration boundary layer was never reached, even for the largest tube. Therefore Sherwood number corresponds to three situations such as – developing concentration boundary layer in mainly hydrodynamic fully developed flow, for low *Re* and long tube lengths, developing concentration boundary layer in partly developing and partly developed flow, for medium *Re* and tube lengths, and developing concentration boundary layer in developing flow, for high *Re* and short tube lengths. But in general, this is a case corresponding to together developing concentration boundary layer and hydrodynamic boundary layers. In Fig. 5, the filled legends show the mass transfer coefficients for the stainless steel tubes with diameter of 0.33 mm. As seen from this figure and

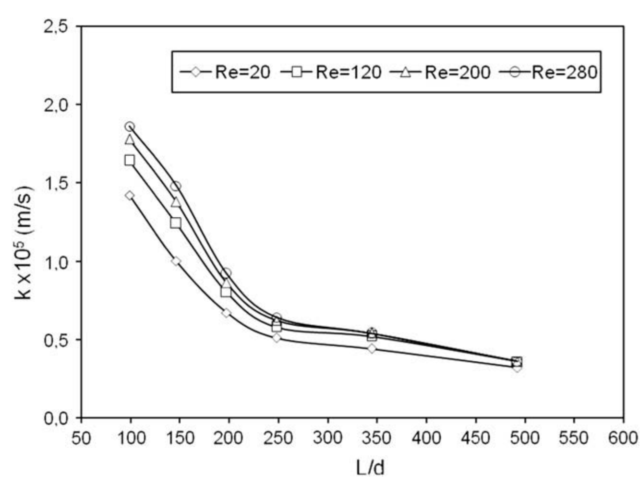

Fig. 6. Variation of mass transfer coefficients with *L*/*d*.

Table 1, although the tubes A and G are approximately in the same length, and B and H have about same length, the mass transfer coefficient of the tubes G and H is lower than A and B, respectively. This can be attributed due to increasing tube diameter. Lee et al. [35] reported that the significant enhancements in heat transfer can be obtained by decreasing the size of the microchannel.

Graetz number for heat transfer is defined by $Gz_H \equiv (\pi/4)(d/L)(Re\,Pr)$ [42]. It is an important parameter in the analysis of the heat transfer phenomena and describes the ratio of the thermal relaxation time (d^2/α) to the transient time (L/u). Therefore, the inversion of Graetz number is a measure of the time that an element of fluid has been in the pipe to the time required for heat to diffuse into it [43]. Similar to heat transfer, Graetz number for mass transfer is defined by $Gz_M \equiv (\pi/4)(d/L)(Re\,Sc)$ [42]. The solution of the energy equation is known as Graetz's problem for hydrodynamically fully developed and a parabolic velocity distribution. Although there is numerical evaluation, the calculation can be made by the use of the following approximate equations for the constant surface temperature [42,43].

$$\overline{Nu} = 3.66 + [(0.085 Gz_H)/(1 + 0.047 Gz_H^{2/3})] \quad Gz_H \le 60 \qquad (12)$$

$$\overline{Nu} = 1.65 Gz_H^{1/3} \quad Gz_H \ge 60 \qquad (13)$$

$$Nu = 1.077 Gz_H^{1/3} \quad Gz_H > 100 \qquad (14)$$

The plot of the average Sherwood numbers versus Graetz numbers for A–H tubes is given in Fig. 7. In this figure, the Nusselt numbers calculated from Eqs. (12)–(14) and those calculated from the some previous correlations for microchannels were also included for comparison reasons. In the calculation of Nusselt number, the Pr was taken as 5. As seen from Fig. 7, the experimental Sherwood numbers are lower than those calculated from Eqs. (12)–(14). First, it should be noted that an exact comparison cannot be made. Because these equations are valid only for defined conditions such as fully developed parabolic velocity profile, constant fluid property, etc., a deviation from these conditions affects the results significantly. For example, as velocity profiles are uniform instead of parabolic, the Nusselt/Sherwood number changes about 60% [42].

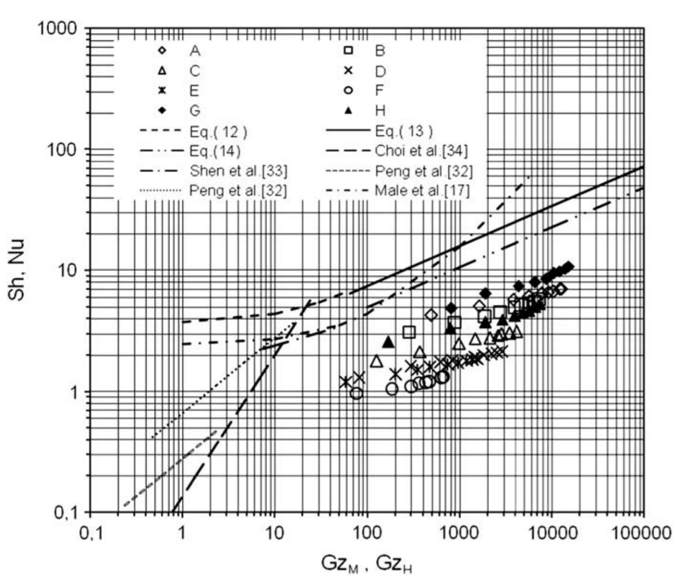

Fig. 7. Variation of Sherwood/Nusselt number with Graetz number.

Similar results have been observed by some researches. As seen from Fig. 7, the values obtained from the correlations suggested by Choi et al. [34], Shen et al. [33], Male et al. [17] and Wang and Peng [32] are also lower than calculated by Eqs. (12)–(14). The behaviour of the results obtained by Sehen et al. [33], Wang and Peng [32] shows similar tendency with the change in Graetz number, while the results by Choi et al. [34] exhibited different behaviour compared to other results, showing stronger dependence on Graetz number. Shen et al. [33] expressed that the deviation from the classical results can be due to the parameters such as surface roughness and channel aspect ratio. The difference in the investigation of Male et al. [17] from the present work is that the mass transfer took place at the top surface of a rectangular system. In the critical review works of published results on the friction factors and convective heat transfer in microchannels given by [10–15,36], it is reported that, in many cases, the experimental results obtained for laminar flow in microchannel present significant deviations from the predictions of the conventional theory and each other. It was found that Nusselt numbers are greater [34,37,38] and lower [39,40] than those obtained conventional correlations. It is claimed that these deviations can be attributed to some parameter such as inlet and outlet effects, surface roughness, non-uniform channel geometry, effect of velocity and thermal boundary, uncertainty of experimental measurements and channel dimension, etc. Nevertheless, it still has not been claimed that heat transfer cannot be predicted by using the classical correlations developed for macrochannels. Furthermore, no mass transfer result in microchannels has been spotted in the literature by the authors for comparison reasons.

The necessary care should be taken for the surface cleanliness in the case of the present measurement technique. Chemical and electrochemical cleaning was only applied; but, since the pipe diameter is too small, mechanical cleaning was impossible. To be able to get an answer to the question why the mass transfer results are lower, it is necessary to get a clue about the surface cleanliness; that is, whether all the entire surface is elctrochemically active or not. Fort his purpose, different pipes made by different companies and different materials were used, including stainless steel needles produced for medical applications. The SS needles have also different ID than nickel pipe. The results are shown in Fig. 7 with filled legends for two different pipe lengths (G and H). As seen from this figure, the results of SS tubes are in reasonable agreement with those of nickel ones. Therefore, the surface cleanliness cannot be the reason for being smaller of the mass transfer. The statistical analysis of the experimental data gave the following correlation for average Sherwood numbers as shown in Fig. 7. For the present work, the power of Graetz number is 0.494.

$$\overline{Sh} = 0.0792 Gz_M^{0.494} \quad r = 0.8829 \qquad (15)$$

The powers of Graetz number show a wide variation in the correlations given in different forms. This value in Eqs. (12) and (13) is 0.33, while for the case of mass transfer from the upper surface of a rectangular system it is 0.835 in laminar flow, and 0.5 for plug flow in the range of $Gz_M^{-1} < 100$ [17].

4. Conclusion

The convective mass transfer and pressure drop in the circular tubes with the diameter of 0.2 mm was investigated. The effect of Reynolds number of the flow and L/d ratio of the tube were studied. The conclusions from the experimental results can be summarized as

- The friction factor is in very good agreement with the Hagen–Poiseuille theory in the laminar regime, and therefore it can be said the conventional correlations can be used to determine the friction factors for microtubes with ID ≥ 0.20 mm.
- Mass transfer experimental results showed that Sherwood number for microtubes is smaller than those obtained from the correlations developed for macrotubes. Further detailed systematic studies are required to get sufficient knowledge of the mass transfer in microtubes.

Acknowledgements

This study was supported financially by TÜBİTAK-MAG (106M304) and partially by Atatürk University (2005/12). The authors would like to thank for their financial support.

References

[1] S.G. Kandlikar, W.J. Grande, Evolution of microchannel flow passages – thermohydraulic performance and fabrication technology, Heat Transfer Engineering 24 (2003) 3–17.
[2] D. Yu, R. Warrington, R. Barron, T. Ameel, An experimental and theoretical investigation of fluid flow and heat transfer in microtubes, in: Proceedings of ASME/JSME Thermal Engineering Conference, Maui, HI, 1995, pp. 523–530.
[3] T.M. Adams, S.I. Abdel-Khalik, S.M. Jeter, Z.H. Quereshi, An experimental investigation of single-phase forced convection in microchannel, International Journal of Heat and Mass Transfer 41 (1998) 851–857.
[4] G.P. Celata, M. Cumo, M. Guglielmi, G. Zummo, Experimental investigation of hydraulic and single-phase heat transfer in 0.130-mm capillary tube, Microscale Thermophysical Engineering 6 (2002) 85–97.
[5] Gh.M. Mala, D. Li, Flow characteristics of water in microtubes, International Journal of Heat and Fluid Flow 20 (1999) 142–148.
[6] Z.X. Li, D.X. Du, Z.Y. Guo, Experimental study on flow characteristic of liquid in circular microtubes, Microscale Thermophysical Engineering 7 (2003) 253–265.
[7] W. Owhaib, B. Palm, Experimental investigation of single-phase convective heat transfer in circular microchannels, Experimental Thermal and Fluid Science 28 (2004) 105–110.
[8] G.L. Morini, M. Lorenzini, S. Salvigni, Friction characteristics of compressible gas flows in microtubes, Experimental Thermal and Fluid Science 30 (2006) 733–744.
[9] C.Y. Yang, T.Y. Lin, Heat transfer characteristics of water flow in microtubes, Experimental Thermal and Fluid Science 32 (2007) 432–439.
[10] C.B. Sobhan, S.V. Garimella, A comparative analysis of studies on heat transfer and fluid flow in microchannels, Microscale Thermophysical Engineering 5 (2001) 293–311.
[11] N.T. Obot, Toward a better understanding of friction and heat/mass transfer in microchannels – a literature review, Microscale Thermophysical Engineering 6 (2002) 155–173.
[12] G.L. Morini, Single-phase convective heat transfer in microchannels: a review of experimental results, International Journal of Thermal Sciences 43 (2004) 631–651.
[13] I. Hassan, P. Phutthavong, M. Abdelgawad, Microchannel heat sinks: an overview of the state-of-the-art, Microscale Thermophysical Engineering 8 (2004) 183–205.
[14] C.B. Sobhan, G.P. Peterson, A review of convective heat transfer in microchannels, Mühendis ve Makina 557 (2006) 10–67.
[15] G.P. Celata, M. Cumo, G. Zummo, Thermal hydraulic characteristics of single-phase flow in capillary pipe, in: Keynote Lecture at the International Symposium on Compact Heat Exchangers, Grenobie, 2002.
[16] R.E. Acosta, R.H. Muller, C.W. Tobias, Transport processes in narrow (capillary) channels, AIChE Journal 31 (1985) 473–482.
[17] P. van Male, M.H.J.M. de Croon, R.M. Tiggelaar, A. van den Berg, J.C. Schouten, Heat and mass transfer in a square microchannel with asymmetric heating, International Journal of Heat and Mass Transfer 47 (2004) 87–99.
[18] R.J. Selman, C.W. Tobias, Mass transfer measurements by the limiting current technique, Advances in Chemical Engineering 10 (1978) 211.
[19] D.A. Szanto, S. Cleghorn, C. Ponce-de-Leon, F.C. Walsh, The limiting current for reduction of ferricyanide ion at nickel: the importance of experimental conditions, AIChE Journal 54 (2008) 802–810.
[20] W.M. Kays, A.L. London, Compact Heat Exchangers, McGraw-Hill, New York, 1984.
[21] P. Gao, S.L. Person, M.F. Marinet, Scale effects on hydrodynamics and heat transfer in two-dimensional mini and microchannels, International Journal of Thermal Sciences 41 (2002) 1017–1027.
[22] J. Judy, D. Maynes, B.W. Webb, Characterization of frictional pressure drop for liquid flows trough microchannels, International Journal of Heat and Mass Transfer 45 (2002) 3477–3489.
[23] P.F. Hao, F. He, K.Q. Zhu, Flow characteristics in trapezoidal silicon microchannel, Journal of Micromechanics and Microengineering 15 (2005) 1362–1368.
[24] S.G. Kandlikar, S. Garimella, D. Li, S. Colin, M.R. King, Heat Transfer and Fluid Flow in Minichannels and Microchannels, Elsevier Ltd, UK, 2006.
[25] R.Y. Chen, Flow in the entrance region at low Reynolds numbers, Journal of Fluid Engineering 95 (1973) 153–158.
[26] J.P. Holman, Experimental Methods for Engineering, fifth ed. McGraw-Hill, New York, 1989.
[27] F.P. Icropera, D.P. DeWitt, Fundamentals of Heat and Mass Transfer, John Wiley and Sons, New York, 1996.
[28] D. Lelea, S. Niio, K. Takano, The experimental research on microtube heat transfer and fluid flow of distilled water, International Journal of Heat and Mass Transfer 47 (2004) 2817–2830.
[29] Y.W. Hwang, M.S. Kim, The pressure drop in microtubes and the correlation development, International Journal of Heat and Mass Transfer 49 (2006) 1804–1812.
[30] D.J. Phares, G.T. Smedley, A study of laminar flow of polar liquids through circular microtubes, Physics of Fluid 16 (2004) 1267–1272.
[31] X.F. Peng, G.P. Peterson, Forced convection heat transfer of single-phase binary mixtures through microchannels, Experimental Thermal and Fluid Science 12 (1996) 98–104.
[32] B.X. Wang, X.F. Peng, Experimental investigation on liquid forced convection heat transfer through microchannels, International Journal of Heat and Mass Transfer 37 (1994) 73–82.
[33] S. Shen, J.L. Ku, J.J. Zhau, Y. Chen, Flow and heat transfer in microchannels with rough wall surface, Energy Conversion and Management 47 (2006) 1311–1325.
[34] S.B. Choi, R.F. Barron, R.O. Warrington, Fluid flow and heat transfer in microtubes, in: Micromechanical Sensors, Actuator and Systems, ASME DSC, vol. 32, Atlanta, GA, 1991, pp. 123–134.
[35] P.-S. Lee, S.V. Garimella, D. Liu, Investigation of heat transfer in rectangular microchannels, International Journal of Heat and Mass Transfer 48 (2005) 1688–1704.
[36] B. Palm, Heat transfer in microchannels, Microscale Thermophysical Engineering 5 (2001) 155–175.
[37] M.M. Rahman, F.J. Gui, Experimental measurements of fluid flow and heat transfer in microchannel cooling passage in a chip substrate, in: Advances in Electronic Packing, ASME EEP, vol. 199, 1993, pp. 685–692.
[38] P. Wu, W.A. Little, Measurements of the heat transfer characteristics of gas flow in fine channel heat exchangers used for microminiature refrigerators, Cryogenics 24 (1984) 415–420.
[39] X.F. Peng, B.X. Wang, Forced convection and flow boiling heat transfer for liquid flowing through microchannels, International Journal of Heat and Mass Transfer 36 (1993) 3421–3427.
[40] X.F. Peng, G.P. Peterson, B.X. Wang, Frictional flow characteristics of water flowing through rectangular microchannels, Journal of Experimental Heat Transfer 7 (1995) 249–264.
[41] M.J. Kohl, S.I. Abdel-Khalik, S.M. Jeter, D.L. Sadowsk, An experimental investigation of microchannel flow with internal pressure measurements, International Journal of Heat and Mass Transfer 48 (2005) 1518–1533.
[42] K. Asano, Mass Transfer from Fundamentals to Modern Industrial Application, Wiley-Vch Verlag GmbH& co. KGaA, Weinheim, 2006.
[43] G.F. Hewitt, G.L. Shires, T.R. Bott, Process Heat Transfer, CRC Press, Boca Raton, 1994.
[44] A.J. Bard, L.R. Faulkner, Electrochemical Methods: Fundamentals and Applications, John Wiley and Sons, New York, 1980.
[45] F.F. Abdelall, G. Hahn, S.M. Ghiaasiaan, S.I. Abdel-Khalik, S.S. Jeter, M. Yoda, D.L. Sadowski, Pressure drop caused by abrupt flow area changes in small channels, Experimental Thermal and Fluid Science 29 (2005) 425–434.