



EXPERIMENTAL STUDY OF SINGLE-PHASE FLUID FLOW AND HEAT TRANSFER CHARACTERISTICS IN RECTANGULAR MICROCHANNELS

Burak MARKAL*, Orhan AYDIN** and Mete AVCI***

* Department of Energy Systems Engineering, Recep Tayyip Erdogan University, 53100 Rize, Turkey, burak.markal@erdogan.edu.tr

** Department of Mechanical Engineering, Karadeniz Technical University, 61080 Trabzon, Turkey, oaydin@ktu.edu.tr

*** Department of Mechanical Engineering, Karadeniz Technical University, 61080 Trabzon, Turkey, mavci@ktu.edu.tr

(Geliş Tarihi: 16.03.2017, Kabul Tarihi: 20.03.2018)

Abstract: In this study, single-phase laminar flow of deionized water through microchannel heat sinks is investigated experimentally. Heat sinks including twenty-nine parallel rectangular channels have been used as the test samples. Three different channel geometries with different aspect ratio ($AR = 1.22, 0.82$ and 0.37) but with the same hydraulic diameter ($100 \mu\text{m}$) are considered. A constant heating power of 9 W is applied to the test section. The range of Reynolds number varies from 12.3 to 47.3 . It is disclosed that increasing AR increases Nusselt number while decreasing the friction factor.

Keywords: Microchannel, single phase, laminar, forced convection, Nusselt number, friction factor

DİKDÖRTGENSEL MİKROKANALLARDA TEK FAZLI AKIŞKAN AKIŞI VE ISI TRANSFERİ KARAKTERİSTİKLERİNİN DENEYSEL İNCELENMESİ

Özet: Bu çalışmada, deiyonize suyun mikrokanallı ısı alıcılardaki tek fazlı laminar akışı deneysel olarak incelenmiştir. Yirmi dokuz paralel dikdörtgen kanallı ısı alıcılar test numuneleri olarak kullanılmıştır. Aynı hidrolik çapa ($100 \mu\text{m}$) fakat farklı boyut oranlarına sahip ($AR = 1.22, 0.82$ and 0.37) üç farklı kanal geometrisi dikkate alınmıştır. Test bölgesine, 9 W olacak şekilde sabit bir ısıtma gücü uygulanmıştır. Reynolds sayısı 12.3 ile 47.3 arasında değişmektedir. Artan AR değerlerinin Nusselt sayısını artırdığı ve sürtünme faktörünü azalttığı görülmüştür.

Anahtar Kelimeler: Mikrokanal, tek faz, laminar, zorlanmış taşınım, Nusselt sayısı, sürtünme faktörü

NOMENCLATURE

A	Cross section area [m^2]
AR	Aspect ratio, $AR = W_{ch}/H_{ch}$
D_h	Hydraulic diameter [m]
h	Heat transfer coefficient [$\text{W m}^{-2} \text{K}^{-1}$]
H	Height [m]
k	Thermal conductivity [$\text{W m}^{-1} \text{K}^{-1}$]
L	Length of microchannel [m]
N	Channel number
Nu	Nusselt number $Nu = h D_h / k_L$
G	Mass flux [$\text{kg m}^{-2} \text{s}^{-1}$]
q''	Heat flux [kW m^{-2}]
q_{loss}	Heat loss [kW]
Re	Reynolds number, $Re = G D_h / \mu$
T	Temperature [K]
\dot{V}	Volumetric flow rate [$\text{m}^3 \text{s}^{-1}$]
W	Width [m]

Greek symbols

f	Fanning friction factor for single-phase liquid flow
μ	Viscosity [Ns m^{-2}]
ΔP	Pressure difference [Pa]
ΔT	Temperature difference [K]
ΔT_{lm}	Logarithmic mean temperature difference, $\Delta T_{lm} = (T_o - T_i) / \ln \left(\frac{T_{w,avg} - T_i}{T_{w,avg} - T_o} \right)$

ρ Density [kg m^{-3}]

Subscripts

avg	Average
ch	Microchannel
f	Frictional
i	Inlet (deep plenum)
L	Liquid, water
o	Exit (deep plenum)
w	Wall

INTRODUCTION

Rapid pace of technology has led to emergence of new research and application areas such as micro electro-mechanical systems, microfluidics and microelectronic. Micro systems or components are used in automotive, defense, biomedical, bioengineering, chemistry, aerospace, computer and many other sectors such as micro pumps, accelerometers, tilt meters, micro thrusters, tyre pressure sensors, glucose sensors, laser diode arrays, microchips and microprocessors. Increasing operational capacities against decreasing dimensions of the electro-mechanical systems causes thermal problems. Therefore, effective heat removing techniques are required for sustainable performance and life expectancy of the equipments. One of the most important thermal management ways is the single phase convective heat transfer in microchannels.

After the pioneering work of Tuckerman and Pease (1981), extensive studies on single-phase convective heat transfer and flow characteristics in microchannel heat sinks have appeared in the existing literature. In microchannel flows, physical mechanism and its affecting parameters considerably differ from those regarding the conventional channels. As stated in Refs. (Herwig and Hausner, 2003; Morini, 2004; Morini, 2006; Rosa et al., 2009; Morini and Yang, 2013), the main difference stems from the scaling effects in microchannels as well as the effect of the measurement/experimental uncertainties. Rosa et al. (2009) listed the scaling effects as entrance effects, temperature dependent properties, rarefaction effects, compressibility effects, conjugate heat transfer, viscous heating, surface roughness and electric double layer (EDL) effects.

In recent years, its aforementioned practical relevance has triggered research interest microscale fluid flow and heat transfer. For the sake of the brevity, here, we limit our literature review to studies on the single-phase liquid flow in rectangular microchannels. Peng et al. (1994a and 1994b) investigated heat transfer and flow characteristics of water through rectangular microchannels with varying aspect ratios and hydraulic diameters. They concluded that decreasing hydraulic diameter decreased transition region (from laminar to turbulent). They stated that increasing channel depth to width ratio increased the friction factor and laminar convective heat transfer reached a maximum when this ratio was equal to 0.75. Harms et al. (1999) investigated single-phase forced convection for the flow of deionized water through single and multiple rectangular channels with hydraulic diameters of nearly 400 μm (251 x 1000 μm^2). For the case of single channel, experimental Nusselt number was found to be higher than the predicted ones for all the flow rates considered. For multiple channel case, the Nusselt number was compatible with the theory only at high flow rates. Xu et al. (2000) investigated flow friction in rectangular

microchannels with hydraulic diameters ranging from 30 μm to 344 μm for the Reynolds number of 20 – 4000. They used deionized water as the working fluid, and their results were compatible with conventional behaviors. Judy et al. (2002) studied frictional pressure drop for the flow of distilled water, methanol and isopropanol in round and square microchannels with diameters of 15 μm – 150 μm . They concluded that experimental results did not significantly deviate from conventional theory for the Reynolds number range of 8-2300. Qu and Mudawar (2002) experimentally and numerically studied single-phase heat transfer characteristics of deionized water flow in parallel rectangular microchannel heat sink. The channel width and depth were 231 μm and 713 μm , respectively, and the Reynolds number ranged from 139 to 1672. They stated that conventional Navier –Stokes and energy equations could be applied to microchannel flows. Popescu et al. (2002) investigated heat transfer for the flow of R-124 in rectangular micro-channels with high aspect ratios. They considered three different channels with the same width of 10 mm but with different depths (128 μm , 263 μm and 521 μm). They concluded that experimental Nusselt numbers for the smallest channel significantly showed deviations from those of conventional theory. Liu and Garimella (2004) experimentally and numerically investigated flow characteristics of deionized water in microchannels with hydraulic diameters between 244 μm and 974 μm . The Reynolds number ranged between 230 and 6500. They concluded that conventional theory was reliable for microchannels. Lee et al. (2005) investigated heat transfer of single-phase flow of deionized water in rectangular microchannel heat sinks with hydraulic diameters from 318 μm to 903 μm . The Reynolds number ranged from 300 to 3500. They stated that heat transfer coefficient increased with decreasing channel size, and the conventional correlations significantly deviated from the experimental results. Hrnjak and Tu (2007) investigated pressure drop characteristics of R-134a in rectangular microchannels with different hydraulic diameters from 69.5 μm to 304.7 μm and aspect ratios from 0.09 to 0.24. Reynolds number ranged from 112 to 9180. They obtained that the friction factor deviated from the conventional theory, which was probably due to the surface roughness. Jung and Kwak (2008) investigated friction factor and heat transfer characteristics of water flow in rectangular microchannels. They stated that there was a linear relationship between the heat transfer coefficient and wall temperature. The Nusselt number-Reynolds number relation deviated from the conventional values obtained for the macrochannel case. However, friction factor in laminar flow was found to be compatible with conventional ones. Park and Punch (2008) experimentally studied single-phase laminar flow of deionized water in microchannels with hydraulic diameters of 106 μm –307 μm . Reynolds number ranged from 69 to 800. They remarked that experimental friction factors were compatible with the ones from conventional theory for fully developed flow, while average Nusselt numbers differed. Hernando et al.

(2009) investigated hydrodynamical and thermal performance of two different micro-heat exchangers consisting of $100 \times 100 \mu\text{m}^2$ and $200 \times 200 \mu\text{m}^2$ microchannels, respectively. They used deionized water as the working fluid. Mokrani et al. (2009) studied fluid flow and convective heat transfer in rectangular microchannels with hydraulic diameters of 100-1000 μm . They used water as the working fluid. They concluded that the results did not deviate from the conventional ones. Parlak et al. (2011) investigated the effect of viscous heating on the single-phase water flow in micro tubes with the diameters between 50 -- 150 μm (experimentally and numerically). They stated that there are temperature increments due to the viscous heating in water flow of smooth micro tube, which should be considered in calculations (especially for smaller tube diameter, longer tube lengths and higher Reynolds numbers). Sehgal et al. (2012) investigated the effect of channel aspect ratio and plenum aspect ratio of microchannel heat sinks on heat transfer and pressure drop of single phase deionized water flow. Respectively, two and three different aspect ratios of channel and plenum were tested under three different flow arrangements for the Reynolds number ranging from 224.3 to 1121.7. They concluded that increasing channel aspect ratio and decreasing plenum aspect ratio increased the Nusselt number. Mirmanto et al. (2012) investigated heat and fluid flow characteristics of single-phase deionized water in three different microchannels with hydraulic diameters of 438 μm , 561 μm and 635 μm . They stated that experimental Nusselt number and friction factor were higher than the conventional values for the fully developed conditions. Zhang et al. (2014) studied the flow and heat transfer characteristics of water flow through multiport tubes with rectangular microchannels. They concluded that entrance effect influenced the friction factor in turbulent region, while roughness had a negligible effect. However, both of the roughness and entrance effect increased Nusselt number. Dai et al. (2014) experimentally and theoretically investigated frictional and heat transfer characteristics of single-phase flow of ethanol through two multi-port micro tubes with rectangular and circular channels with Reynolds number ranging from 50 to 2400. They stated that Nusselt number decreased with increasing inlet temperature and heat flux. They obtained that conjugate heat transfer, entrance effects and viscosity variation with temperature played effective roles on heat transfer.

As it is summarized above, there is a consistency or an inconsistency between the results for microscale and macroscale (conventional). This is an ongoing debate (Rosa et al., 2009), as successfully reviewed by Dey et al. (2012). The readers are referred to see some review articles (Sobhan and Garimella, 2001; Morini, 2004; Steinke and Kandlikar, 2006; Rosa et al., 2009; Dey et al., 2012; Morini and Yang, 2013) for a detailed explanation.

As stated above, single-phase liquid flow in microchannel heat sinks is one of the most important

cooling techniques used in the thermal management of high thermal-density compact systems. The effect of geometrical parameters on heat transfer and flow characteristics should be carefully addressed for an optimum microchannel design. Therefore, in this article, it is aimed to investigate the effect of aspect ratio on heat transfer and frictional characteristics of single-phase laminar flow of de-ionized water in microchannels. Each of three heat sinks contains twenty nine parallel straight rectangular microchannels. For a precise and correct determination of AR effect, all microchannels were designed with the same hydraulic diameter. In this regard, this is the first study in the literature to the best of our knowledge.

EXPERIMENTAL STUDY

Figure 1 illustrates the schematic of the experimental set-up. The deionized water is used as the working fluid, which is pumped through the system by a micro gear pump (Cole Parmer TW-07002-25 Micropump®) with a digital driver (Ismatec® compact programmable digital drive, Cole Parmer TW-78008-10). In the system, a constant temperature bath (LABO DX-300) is used for controlling the inlet temperature of the working fluid. Figure 2 shows the test section. It includes the following components: PTFE (Polytetrafluoroethylene) housings, a copper block, a transparent polycarbonate cover plate, ceramic cloth, sealing materials and a microchannel heat sink. The silicon microchannel heat sinks with a length of 48 mm and a width of 13.5 mm including twenty nine parallel rectangular channels were used. Inlet and outlet temperatures of the water as well as the surface temperature of the heat sink are measured using thermocouples. Four cartridge heaters connected to a power supply (Agilent 6812B) are used to heat the system. More details of the test section, product names and codes of the all equipments/devices and heat loss calibration were stated in an earlier work of the authors (Markal et al., 2016). The geometric dimensions of the microchannels in each heat sink are given in Table 1. For the uncertainty analysis, the method of Kline and McClintock (1953) has been followed. The uncertainties were obtained as 2.2-3.5 % for Nusselt number and 3.2-8.5 % for the friction factor. Also, the uncertainties related to the measured values are given in Table 2. The experiments were repeated at least two times to verify reproducibility of the experimental data.

DATA REDUCTION

The Reynolds number is defined as;

$$\text{Re} = \frac{GD_h}{\mu} \quad (1)$$

where D_h and μ represent the hydraulic diameter and the viscosity, respectively, while G denotes the mass flux.

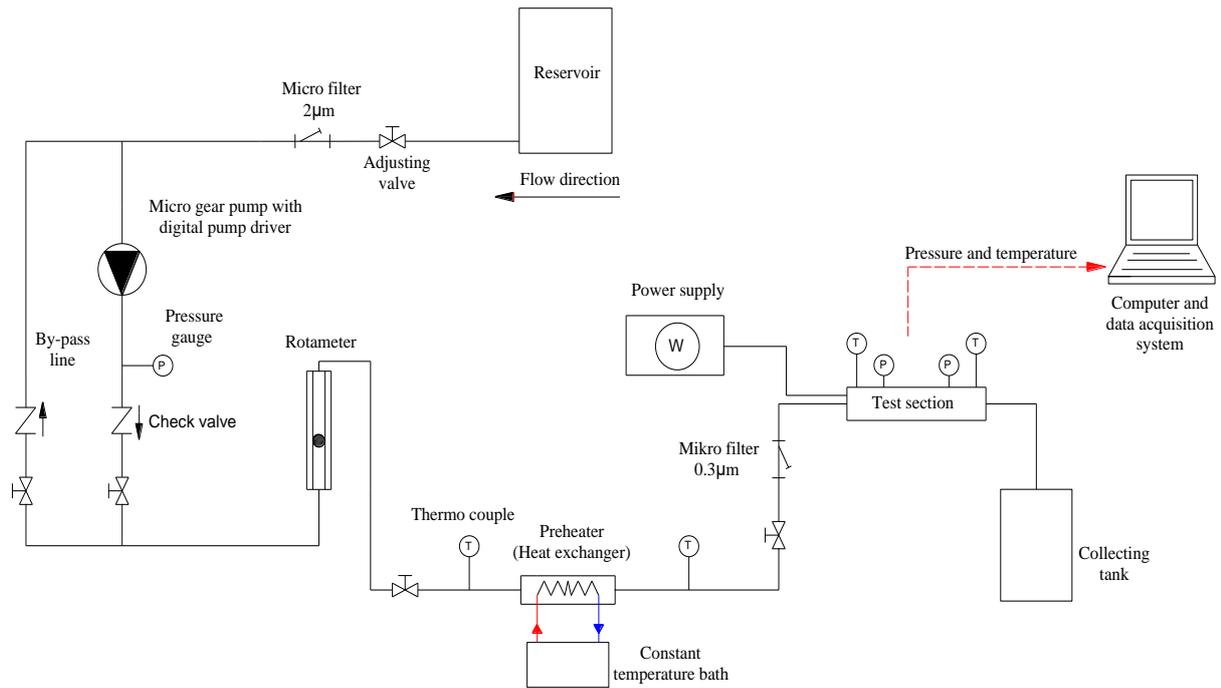


Figure 1. The schematic of the experimental set-up.

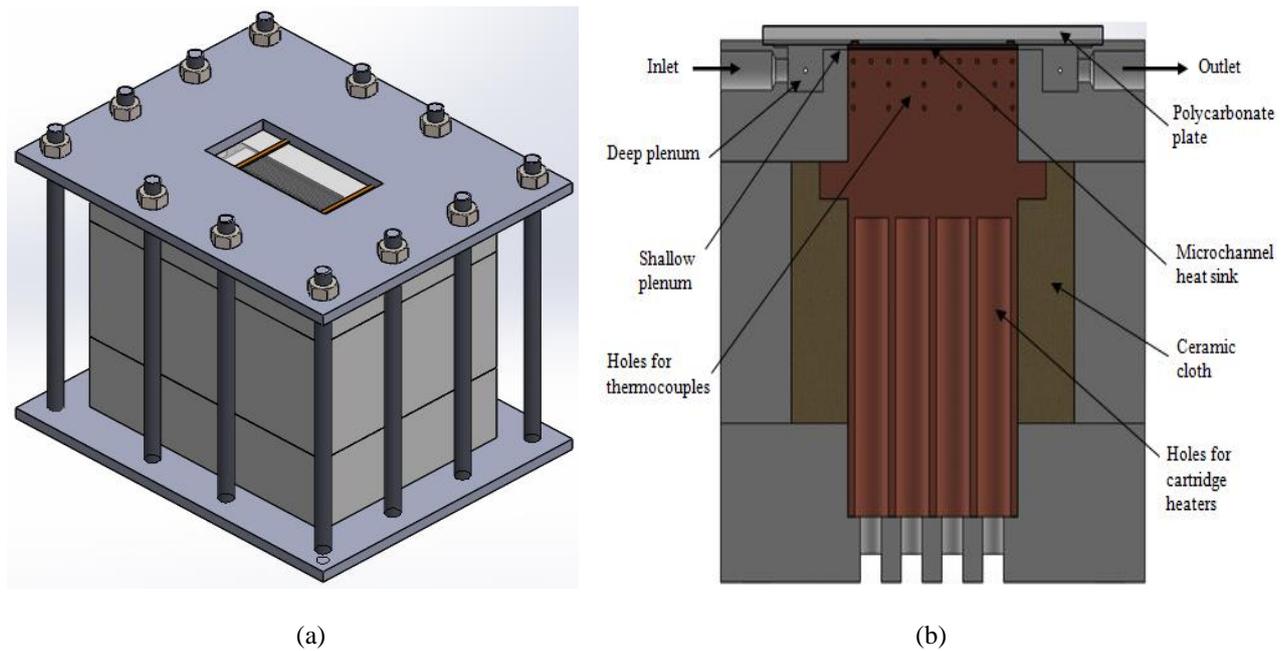


Figure 2. Complete (a) and the sectional view (b) of the test section

Table 1. Geometric dimensions of microchannels.

No	Channel width, W_{ch} (μm) $\pm 0.1 \mu\text{m}$	Channel depth, H_{ch} (μm) $\pm 0.1 \mu\text{m}$	Aspect ratio, AR	Hydraulic diameter, D_h (μm)
1	70	190	0.37	100
2	90	110	0.82	100
3	110	90	1.22	100

Table 2. Uncertainties of the measured values.

Measurements	Uncertainty
Pressure	$\pm 0.25 \%$
Temperature	$\pm 0.1 \text{ }^\circ\text{C}$
Flow rate	$\pm 2.0 \%$
Applied power	$\pm 0.1 \%$

Mass flux is given as follows:

$$G = \frac{\dot{V}\rho_L}{NA_{ch}} \quad (2)$$

where \dot{V} is the volumetric flow rate, ρ_L is the liquid density, N is the channel number and A_{ch} is the cross sectional area of a microchannel. From the Newton's cooling law, the average heat transfer coefficient is described as in the following:

$$h_{avg} = \frac{q_w''}{\Delta T_{lm}} \quad (3)$$

where q_w'' is the heat flux applied at the channel wall and ΔT_{lm} is the logarithmic-mean temperature difference, which is defined as in the following:

$$\Delta T_{lm} = \frac{(T_o - T_i)}{\ln\left(\frac{T_{w,avg} - T_i}{T_{w,avg} - T_o}\right)} \quad (4)$$

The channel wall heat flux, local wall temperature and relevant equations were given in Ref. (Markal et al., 2016) in a detailed manner. The average wall temperature is calculated as the arithmetic mean of the microchannel local wall temperatures. The average Nusselt number can be defined as;

$$Nu_{avg} = \frac{h_{avg}D_h}{k_L} \quad (5)$$

where k_L represents the thermal conductivity of water. The friction factor can be determined from

$$f = \frac{\Delta P_f D_h \rho_L}{2LG^2} \quad (6)$$

where ΔP_f is the frictional pressure loss (through the channels). It is obtained by subtracting the constriction pressure loss and expansion pressure recovery components from the total pressure drop. The explicit forms of all the relevant components were defined in the previous study of the authors (Markal et al., 2016). Here, the only difference is that the vapor quality should be taken zero due to the single phase flow.

RESULTS AND DISCUSSION

Experiments were conducted for five different values of the flow rate (2, 3, 4, 5 and 6 ml/min) corresponding to the range of Reynolds number from 12.3 to 47.3. A constant heating power of 9 W was applied for all the cases tested. To validate the accuracy of the experimental results, the Nusselt number values determined are compared against those predicted using the correlation proposed by Peng and Peterson (1996). Figure 3 depicts that our results agree very well with that correlation of which the range of deviation is defined approximately as $\pm 30\%$ (see Peng and Peterson (1996)).

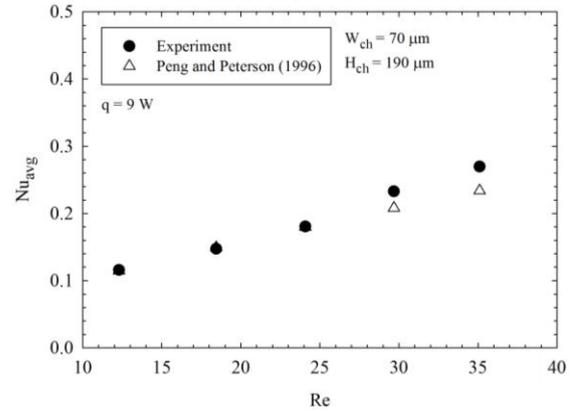


Figure 3. Comparison of experimental results with those obtained using the correlation of Peng and Peterson (1996).

For different values of the aspect ratio, the variation of the Nusselt number with Reynolds number is illustrated in Fig. 4. For any value of AR considered, Nusselt number increases with Reynolds number, as expected. As it is seen that increasing AR results in an increase in Nusselt number. The aspect ratio is defined as the ratio of the channel width to channel depth (height). Therefore, increasing AR decreases the total heat transfer area of microchannel. Therefore, for a constant value of the heat input, increasing AR will increase the channel wall heat flux. These results are compatible with the those given by Peng et al. (1994a and 1994b). They obtained maximum value of the Nusselt number at AR = 1.33 (as channel width to depth ratio). Similarly, here, Nusselt number shows enhancement trend towards AR = 1.22.

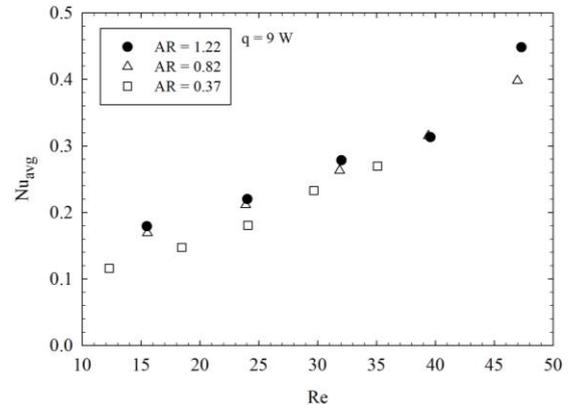


Figure 4. The variation of Nu with Re number for varying values of AR.

Pumping power requirement is a serious limiting factor in fluid systems, especially for micro systems. Thus, relevant geometrical arrangements should be made to reduce the friction factor. Figure 5 shows the variation of the friction factor with the Reynolds number for various values of AR. As it is seen from the figure, the friction factor decreases with an increase in AR. This could be attributed to the surface roughness and thus, to the wetted area of the channels. In these geometrical arrangements, the largest wetted area belongs to the channels with the smallest aspect ratio. As a natural consequence of the micromachining technique used in the manufacturing of the microchannels (deep reactive ion etching / Bosch process), sidewalls have higher roughness than the bottom. Sidewall area decreases with increasing aspect ratio. As it is expected, decreasing contact surface causes lower friction. Thus, increasing aspect ratio has positive impact on pumping power. Unsurprisingly, friction factor decreases with Reynolds number for any AR value considered. The relation between the surface roughness and the friction factor was also emphasized by Hrnjak and Tu (2007) such that they explained it as the reason of deviation from the conventional theory.

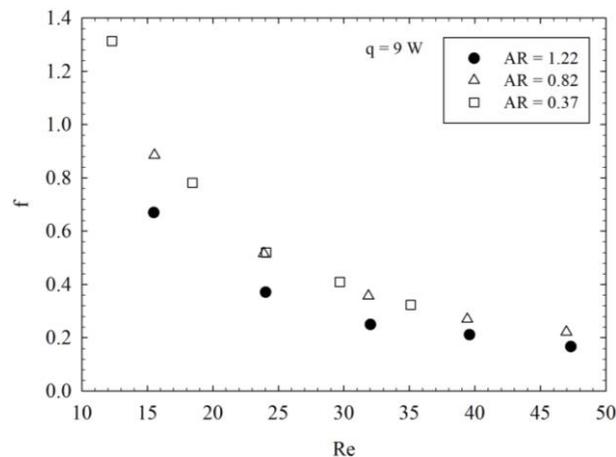


Figure 5. The variation of the friction factor with Reynolds number for varying values of AR.

Besides the above trends, it should be noted that obtained results are significantly deviates from the conventional theory. The deviations in the heat transfer and/or flow characteristics were also indicated by lots of studies such as (Peng et al., 1994a and 1994b; Popescu et al., 2002; Lee and Garimella, 2005; Hrnjak and Tu, 2007; Jung and Kwak, 2008; Park and Punch, 2008; Sehgal et al., 2012; Mirmanto et al., 2012; Dai et al., 2014). Figure 6a and b show the comparison of the experimental Nusselt number and friction factor with the ones obtained from the conventional theory, respectively. As seen from the Fig. 6, both of the experimental Nusselt number and the friction factor are lower than the conventional ones. The comparison is performed against the results of the theory from Incropera et al. (2007), Table 8.1 (page, 519). These results can be attributed to the scale effects, especially to surface roughness and conjugate heat transfer.

Similar emphasis was laid by Dai et al. (2014) who underlined the importance of scale effects.

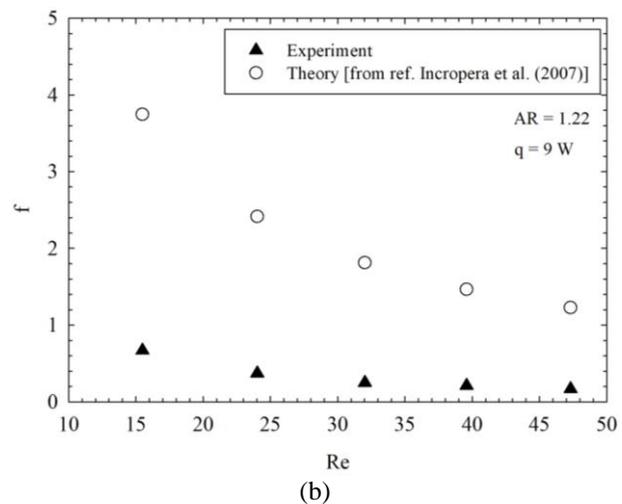
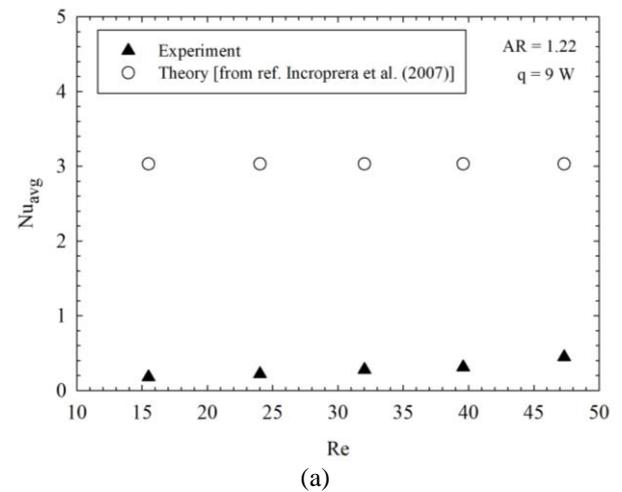


Figure 6. Comparison of the experimental results with the theory: Nusselt number (a) and friction factor (b).

CONCLUDING REMARKS

In this study, single-phase laminar flow of deionized water in rectangular microchannels was examined experimentally. Determining the effect of the aspect ratio on heat transfer and flow characteristics was the focus interest of the study. The main findings of the present study can be summarized as follows:

- Increasing the aspect ratio increases the Nusselt number while it decreases the friction factor.
- For any value of the aspect ratio tested, an increase in the Reynolds number is shown to increase Nusselt number while it decreases the friction factor.
- Both of the experimental Nusselt number and the friction factor are found to be lower than the conventional ones.
- With regards to the scale effects, further studies should be performed for a better addressing of the regarding effects.

REFERENCES

- Dai B., Li M., Dang C., Ma Y. and Chen Q., 2014, Investigation on Convective Heat Transfer Characteristics of Single Phase Liquid Flow in Multi-Port Micro-Channel Tubes, *Int. J. Heat Mass Transfer*, 70, 114 – 118.
- Dey R., Das T. and Chakraborty S., 2012, Frictional and Heat Transfer Characteristics of Single-Phase Microchannel Liquid Flows, *Heat Transfer Eng.* 33, (4-5) 425- 446.
- Harms T.M., Kazmierczak, M.J. and Gerner F.M., 1999, Developing Convective Heat Transfer in Deep Rectangular Microchannels, *Int. J. Heat Fluid Flow*, 20 (8), 149 - 157.
- Hernando N.G., Iborra, A.A., Rivas U.R. and Izquierdo M., 2009, Experimental Investigation of Fluid Flow and Heat Transfer in a Single-Phase Liquid Flow Micro-Heat Exchanger, *Int. J. Heat Mass Transfer*, 52, 5433 – 5446.
- Herwig H. and Hausner O., 2003, Critical View on “New Results in Micro-Fluid Mechanics”: an Example, *Int. J. Heat Mass Transfer*, 46, 935-937.
- Hrnjak P. and Tu X., 2007, Single Phase Pressure Drop in Microchannels, *Int. J. Heat Fluid Flow*, 28, 2-14.
- Incropera P.F., DeWitt P.D., Bergman L.T. and Lavine S.A., 2007, *Fundamentals of heat and mass transfer*, (Sixth Ed.), John-Wiley & Sons Inc, USA.
- Judy J., Maynes, D. and Webb B.W., 2002, Characterization of Frictional Pressure Drop for Liquid Flows Through Microchannels, *Int. J. Heat Mass Transfer*, 45, 3477 – 3489.
- Jung J.Y. and Kwak H.Y., 2008, Fluid Flow and Heat Transfer in Microchannels with Rectangular Cross Section, *Heat Mass Transfer* 44, 1041-1049.
- Kline S.J. and McClintock F.A., 1953, Describing Uncertainties in Single-Sample Experiments, *Mech. Eng.*, 73 (1), 3–8.
- Lee P.S., Garimella S.V. and Liu D., 2005, Investigation of Heat Transfer in Rectangular Microchannels, *Int. J. Heat Mass Transfer*, 48, 1688-1704.
- Liu D. and Garimella S.V., 2004, Investigation of Liquid Flow in Microchannels, *J. Thermophysics and Heat Transfer*, 18 (1), 65 – 72.
- Markal B., Aydin, O. and Avci, M., 2016, Effect of Aspect Ratio on Saturated Flow Boiling in Microchannels, *Int. J. Heat Mass Transfer*, 93, 130-143.
- Mirmanto M., Kenning D.B.R., Lewis J.S. and Karayiannis T.G., 2012, Pressure Drop and Heat Transfer Characteristics for Single-Phase Developing Flow of Water in Rectangular Microchannels, *Journal of Physics: Conference Series* 395, 012085.
- Mokrani O., Bourouga B., Castelain C. and Peerhossaini H., 2009, Fluid Flow and Convective Heat Transfer in Flat Microchannels, *Int. J. Heat Mass Transfer*, 52, 1337 – 1352.
- Morini G.L., 2004, Single-Phase Convective Heat Transfer in Microchannels: a Review of Experimental Results, *Int. J. Therm. Sci.*, 43 631-651.
- Morini, G.L., 2006, Scaling Effects for Liquid Flows in Microchannels, *Heat Transfer Eng.* 27 (4) 64 – 73.
- Morini G.L. and Yang Y.H., 2013, Guidelines for the Determination of Single-Phase Forced Convection Coefficients in Microchannels. *J. Heat Trans.*, 135, 1-10.
- Park H.S. and J. Punch, 2008, Friction Factor and Heat Transfer in Multiple Microchannels with Uniform Flow Distribution, *Int. J. Heat Mass Transfer*, 51, 4535 – 4543.
- Parlak N., Gür M., Engin T. and Küçük H., 2011, Investigation of the Viscous Heating Effect at Single-Phase Laminar Water Flow in Microtubes, *J. of Thermal Science and Technology*, 31,2, 1-11.
- Peng X.F., Peterson G.P. and Wang B.X., 1994a, Frictional Flow Characteristics of Water Flowing Through Rectangular Microchannels, *Exp. Heat Trans.: a Journal of Thermal Energy Generation, Transport, Storage, and Conversion*, 7 (4), 249-264.
- Peng X.F., Peterson G.P. and Wang B.X., 1994b, Heat Transfer Characteristics of Water Flowing Through Microchannels, *Exp. Heat Trans: A Journal of Thermal Energy Generation, Transport, Storage, and Conversion*, 7 (4) 265-283.
- Peng X.F. and Peterson G.P., 1996, Convective Heat Transfer and Flow Friction for Water Flow in Microchannel Structures, *Int. J. Heat Mass Transfer*, 39 (12), 2599-2608.
- Popescu A., Welty J.R., Pfund D. and Rector D., 2002, Thermal Measurements in Rectangular Microchannels, in: Proceedings of IMECE2002, ASME International Mechanical Engineering Congress & Exposition, November 17-22, 2002, New Orleans, Louisiana, IMECE2002-32442.
- Qu, W. and Mudawar, I., 2002, Experimental and Numerical Study of Pressure Drop and Heat Transfer in a Single-Phase Micro-Channel Heat Sink, *Int. J. Heat Mass Transfer*, 45 (12), 2549 – 2565.
- Rosa P., Karayiannis, T.G. and Collins, M.W., 2009, Single-Phase Heat Transfer in Microchannels: The Importance of Scaling Effects, *Applied Thermal Eng.*, 29 3447-3468.

Sehgal S.S., Murugesan K. and Mohapatra S.K., 2012, Effect of Channel and Plenum Aspect Ratios on the Performance of Microchannel Heat Sink Under Different Flow Arrangements, *J. Mechanical Science and Technology*, 26 (9), 2985 – 2994.

Sobhan C.B. and Garimella S.V., 2001, A Comparative Analysis of Studies on Heat Transfer and Fluid Flow in Microchannels, *Microscale Thermophysical Eng.* 5 (4), 293-311.

Steinke M.E. and Kandlikar S.G., 2006, Single-Phase Liquid Friction Factors in Microchannels, *Int. J. Therm. Sci.* 45, 1073-1083.

Tuckerman D.B. and Pease R.F.W., 1981, High-Performance Heat Sinking for VLSI, *IEEE Electron Dev. Lett.*, 2 (5) 126-129.

Xu B.; Ooi, K.T. and Wong, N.T., 2000, Experimental Investigation of Flow Friction for Liquid Flow in Microchannels, *Int. Comm. Heat Mass Transfer*, 27 (8), 1165-1176.

Zhang J., Diao Y.H., Zhao Y.H. and Zhang, Y.N., 2014, An Experimental Study of the Characteristics of Fluid Flow and Heat Transfer in The Multiport Microchannel Flat Tube, *Appl. Therm. Eng.*, 65, 209-218.



Burak MARKAL is an assistant professor in Energy Systems Engineering Department at Recep Tayyip Erdogan University. His research interests cover flow boiling in microchannels, jet flows – impinging jets, fluid flow and heat transfer in microsystems, heat pipes, micro fluidics, electronics cooling, vortex tubes and swirling flows.



Orhan AYDIN is a professor in the Mechanical Engineering Department at Karadeniz Technical University, Trabzon, Turkey. His research interests cover microfluidics, electronics cooling, biological flows, heat and mass transfer, thermal energy storage, transport phenomena in porous media, non-Newtonian fluid dynamics, natural and mixed convection in enclosures, and experimental and numerical heat and fluid flow. He has co-authored more than 150 refereed journal and conference publications. He is the recipient of the Successful Young Scientist Reward from the Turkish Academy of Sciences (TUBA) and the Junior Science Award from the Scientific and Technological Research Council of Turkey (TUBITAK).



Mete AVCI is an associate professor in the Mechanical Engineering at Karadeniz Technical University of Trabzon, Turkey. He received his Ph.D. in mechanical engineering in 2008 from Karadeniz Technical University. His research interests include heat and mass transfer in microchannels, thermal energy storage, non-Newtonian fluid dynamics and transport in porous media.