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A review of single-phase pressure drop characteristics microchannels with bends

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Abstract

Microfluidic use in various innovative research, many fields aimed at developing an application device related to handling fluid flows in miniature scale systems. On the other hand, on the use of micro-devices for fluid flow the existence of bends cannot be avoided. This research aims to make a comprehensive study of fluid flow characteristics through a microchannel with several possible bends. This study was conducted by comparing Reynolds number versus pressure drop in a serpentine microchannel to gain bends loss coefficient. The result showed that the fluid flow with Re < 100 did not affect the pressure drop, but on the Reynolds number above that, the pressure drop was increased along with the appears of vortices in the outer and inner walls around the channel bends which causes an increase in an additional pressure drop. The other finding shows that the reduction in diameter bend tube can increase the pressure drop.

Keywords: pressure drop; bend loss coefficient; single-phase; microchannel bends.

I. Introduction

In recent years, microfluidic tracts have been considerably used in various fields of both engineering and non-engineering. The utilization has also been done as in the heat exchanger for computer CPU coolers [1], fuel cell generators [2][3], micro-mixing reactors [4][5], etc. Regardless of its utilization, the microfluidic system cannot avoid the existence of channel bends which have either negative or positive effects. Therefore, it is considered necessary to study the characteristics of the fluid flow in a miter bend microchannel. Fluid flows in microchannels are analyzed using the Navier-Stokes equations [6][7] and Direct Simulation Monte Carlo [8][9]. This study was conducted by comparing Reynolds number versus pressure drop in a serpentine microchannel with 900 bend and 1800 bends to obtain the bends loss coefficient. Another micro-scale effect observation showed that geometry variations of a channel in bends can cause significant additional pressure drop on the fluid flow [10][11]. This work showed that the fluid flow with a low Reynolds number does not affect the pressure drop. But at the high Reynolds number, the pressure drop increases with the occurrence of vortices in the outer and inner walls around the channel bends causes an increase in the additional pressure drop [12]. Whereas at Re above 1000 the bend loss coefficient Kb almost remains constant and change in the range of ±10 %. The other finding shows that a reduction in diameter bend tube can increase the pressure drop [13][14]. Papautsky [15] presents experimental findings in the domain of single-phase internal fluid flow at the microscale [16].

This review paper investigates experimental data currently available and assesses the current state-of-the-art. Because the majority of microfluidic bends studies conducted on fluid flows in the laminar regime therefore pressure drop constraints, only laminar data are presented here. Furthermore, a small amount of turbulent data is available for the associated pressure drops.

II. Materials and Methods

Surface roughness and friction factors have been affected the characteristic of fluid flow in a channel

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including in the microchannel. Therefore, this section will provide a brief understanding before mainly discuss about pressure drop, and fluid flow characteristics in the microchannel with bends.

A. Surface roughness

Kandlikar *et al.* [17] conducted an experimental investigation on the surface roughness effect in stainless steel microtube with an inner diameter of 620 µm and 1067 µm at Reynolds number range of 500 to 3000. They reported that the surface roughness greatly influences the value of heat transfer and pressure drop. Xing *et al.* [18] performed studies to see how surface roughness affects flow characteristics in 44 circular microchannels by 10 mm in length and a diameter of 400 µm for Reynolds number ranges through 150 to 2800. The essential Reynolds number for a conduit with an inner diameter of 400 m was calculated to be around 1500, and the friction factor effect was increased during the surface roughness escalation. Toghraie *et al.* [19] investigated the effect of surface roughness to pressure drop in a triangle, rectangular, and trapezoidal cross-section microchannel with number roughness of 3, 6 in the Reynolds number of 5, 10, 15, and 20. They concluded that escalating roughness number would escalate the pressure drop in consequence stagnation effect. Jafari *et al.* [20] experimentally investigated the effect of the surface roughness of rectangular microchannel evaporator with 700 µm height, and 250 µm width using R134a as the working fluid. They demonstrate that, as the surface roughness increase from 2.03 µm – 15.86 µm, the heat transfer coefficient was increased up to 45 %.

Some studies conducted a simulation, as, Guo *et al.* [21] which numerically modeled the effect of roughness on the fluid flow in the microchannel under laminar flow. They were studied with 2D and 3D Gauss’ s model where, the 2D model fails to express effect roughness and 3D model is presented sensitively face morphology for both heat transfer and flow resistance. Valde’s *et al.* [22][23] studied numerical simulation and CFD simulation on the effect of surface roughness on the laminar fluid flow through the annular microchannel. Sadaghiani and Kosar [24] investigated numerically an effect of pin fin shape and surface roughness on heat transfer and gas flow in a rough microchannel. They reported that roughness elements causing Nusselt number decline and pressure drop increase, as well as surface roughness reduces pin fin shape effect. Lu *et al.* [25] studied numerically the effect of 2 % roughness in wall square, wave, and limped microchannel with Reynolds number of 500. They showed pressure drop and Nusselt number increase, which also affects the roughness depending on the microchannel's physical shape.

Hydraulic diameter for rectangular cross-section channels determined with:

$$d_h = \frac{4ab}{2(a+b)} \tag{1}$$

Canal aspect ratio, is determined as:

$$\alpha = \frac{a}{b} \tag{2}$$

when referring to laminar theory as a common observation of differences.

$$C^* = \frac{(f\,\mathrm{Re})_{experimental}}{(f\,\mathrm{Re})_{theoretical}} \tag{3}$$

where $f\mathrm{Re}$ is the non-dimensionalized that experimentally and theoretically calculated depending on the cross-section for laminar flow First point.

B. Friction factor

Judy *et al.* [26] performed several experiments with pressure-driven liquid in a round and square microchannel of diameter 15 -150 µm with materials of fused silica and stainless steel using distilled water, methanol, and isopropanol for working fluid in the Reynolds number range 8 to 2300. They concluded that the experimental uncertainty occurred when non-Stokes phenomena were within the diameter ranges. Wu and chang [27] experimented to measure friction factor laminar flow in trapezoidal smooth silicon microchannel with a hydraulic diameter of 25.9 to 291 µm using deionized water for working fluid. They suggested that Navier-Stokes equations are appropriate for deionized liquid flow in microchannel. Morini *et al.* [28] conducted an analytical investigation of rarefaction influence on pressure drop incompressible fluid flow in silicon rectangular, trapezoidal, and double-trapezoidal microchannels. They reported that on condition Mach number under 0.3 the effect of gas rarefaction can be separated from compressibility effect and the behavior of the coefficient α vs a function of the microchannel aspect ratioγ for the three cross -sections. Silverio and Moreira [29] measured the pressure drop and pressure distribution in circular and square microchannels made of borosilicate glass with hydraulic diameter from 50 to 500 µm in the Reynolds number range from 10 to 2500. Zing Li *et al.* [30] conducted a computational and experimental investigation on friction factor of gas flow in microchannel with a diameter from 146.7 – 203 µm. They concluded that friction factor and Reynolds number are not in accordance with Moody chart when Mach number is not more than 0.3. Hong *et al.* [31] studied experimental in friction factor turbulent stream gas in rectangular microchannel made silicon and capped glass with a hydraulic diameter of 99.36 and 146.76 µm. They declared that the friction factor could be expressed with a Blasius correlation and Mach number [32][33].

In the entrance section, the friction factor, f_{exp} was decided using the pressure difference as follows:

$$f_{\exp} = \frac{2\Delta P}{\rho V^2}\frac{D_h}{L} \tag{4}$$

where ΔP is the pressure difference, L is the length device, and V is the mean velocity determined from the mass flow rate. For laminar flow, the theoretical Poiseuille number, $Po = f\text{Re}$ is constant, which is a function of α for rectangular cross-section channel.

Shen *et al.* [34] experimental investigation of deionized water flow in 26 rectangular microchannels with a width of 300 µm and a depth of 800 µm, it flowed in the Reynolds number rangeing from 162 to 1257 and temperatures inlet of 30, 50, and 70 °C. They declared that higher inlet deionized water temperature can give better relatively flow performance, and shown that the predicted friction factor value was higher when the Reynolds number is low. In order to define friction factor flow in microchannels, Celata *et al.* [35] investigated viscous heating. They expressed that microchannels with a diameter below 100 µm using pressure measurements and evaluation viscous heating be validated friction factor. Gunnasegaran *et al.* [36] numerically studied on laminar flow of water in a triangle, rectangular, and trapezoidal cross-section microchannel in the Reynolds number range of 100 – 1000. They reported that the friction factor and Reynolds number effect appear significant on the rectangular channel. Park and Punch [37] conducted an experimental investigation on friction factor and heat transfer in the rectangular microchannel with hydraulic diameter from 106 – 307 µm in the Reynolds number range of 69 – 800. They concluded that the experiment friction factor accord with conventional hydraulic theory, but the heat transfer experimental deviated with Nusselt number from conventional heat transfer theory. Ding *et al.* [38] conducted an experimental investigation on heat transfer and friction factors in a triangular and rectangular microchannel with the hydraulic diameters of 400 and 600 µm using R12 and R134a for working fluid. It is worth noting that the friction factor of both fluids is the same in laminar flow and R12 higher in the turbulent flow.

III. Results and Discussions

A. Pressure drop

Table 1 shows selected literature for single-phase flow in microchannel. Pfund *et al.* [39] measured friction and pressure drop in a rectangular microchannel with a depth range from 128 to 521 µm in range of 60 – 3450 Reynolds numbers. They showed that the Reynolds number decreases with decreasing microchannel depth. Bahrami *et al.* [40] studied the predispose of wall coarseness incompressible laminar flow in a coarse circular microchannel. They reported that the effect of roughness increases the pressure drop but that below 3 % can be neglected. Hwang and Kim [41] investigated on the pressure drop in circular stainless steel microchannel with an inner diameter of 244, 430, and 792 µm when the working fluid is R-134a and the Reynolds number is less than 1000. They make an impression that the first of the flow transition showed a little less than 2000, but on two-phase flow increased the pressure drop with

Table 1.
Selected literature for single-phase flow in microchannel

Author	Year	Fluid/ Form	Shape	D_h (µm)	$\alpha \approx a/b$	*Re*	C^*	*f. Re*	L/D_h	Remarks
Pfund *et al.* [39]	2000	Water/ Liquid	R	253-990	19.19-78.13	55.3-3501	0.01-1.81	0.01-1.81	101-396	The essential Reynolds number decreases as channel depth decreases. In microchannels, the transition is abrupt but not abrupt.
Judy *et al.* [26]	2002	Water, methanol, isopropyl	C,R	14-149	1.00	7.6-2251	0.83-1.27	0.83-1.27	1203-5657	For rectangular channels, pedictions of friction factors are in good agreement with established theories. The material used to construct the microchannel and the test fluid have an impact on the friction factor.
Wu and Cheng [27]	2003	Water/ Liquid	T	169	1.54-26.20	16-1378	0.58-1.88	0.58-1.88	192-467	-
Shen et al. [34]	2006	Water/ Liquid	R	436	2.67	162-1257	1-2.84		16-754	In rough microchannels, surface roughness has a substantial influence on laminar flow. The value of *f*Re is greater than what the standard theory predicts for high Reynolds number values, and it grows with increasing Re
Steinke *et al.* [44]	2006	Water/ Liquid	R	227	0.8	14-789	1.15-3.75		45	The channel cross-section measurements account for the majority of the uncertainty in *f.Re.*
Hrnjak and Tu [43]	2007	R134a/ Liquid	R	69.5-304.7	0.09-0.24	112-9180	1.02-1.09		315-691	In microchannels, surface roughness raises the friction factor and impacts the transition from laminar to turbulent flow
Yuan *et al.* [18]	2016	Water/ liquid	C	400	-	150-2800	-	-	25	The friction factor increase when surface roughness increased
Jafari *et al.* [20]	2016	R134a	R	368	2.8	15.8-36.8	-	-	52	Heat transfer experiment increase 45%

^{C} circular ; ^{R} rectangular; ^{T} trapezoid decreasing inner diameter and increasing quality and mass flux. Bahrami *et al.* [40] conducted some experimentally and numerically analysis on pressure drop of laminar flow in a smooth microchannel with an arbitrary cross-section. They showed that pressure drop from modeling is relatively the same with a numerical analytic result at only an 8 % difference. Qu *et al.* [42] conducted computational and experimental studies on the water flow and pressure drop in the rectangular microchannel with 222 μm of width, 694 μm of depth and 120 mm in the Reynolds number range from 196 – 2215. They show that the suitability of computational and experimental results also proved the conventional Navier-Stokes equation available to predict liquid flow in micro-cooling heat sinks. Hrnjak and Tu [43] studied an investigation on fluid and steam flow in the rectangular microchannel with hydraulic diameter from 69.5 to 304.7 μm in the Reynolds number range of 112 – 9180 using R 134a liquid and steam for working fluid. They concluded that both flow in laminar suitable with the analytical solution but on turbulent flow the friction factor higher than analytical solution.

Steinke and Kandlikar [44] determine factor of friction using the fully established flow and Hagenbach factor, as:

$$\Delta\rho = \frac{2\left(f_{\mathrm{Re}}\right)\mu\bar{V}L}{D_h^2} + \frac{\kappa(x)\rho\bar{V}^2}{2} \tag{5}$$

where is the Hagenbach factor, determined by:

$$\kappa(x) = \left(f_{app} - f_{FD}\right)\frac{4x}{D_h} \tag{6}$$

where f_{FD} is a fully developed friction factor, then total pressure drop component determines, as:

$$\Delta\rho = \frac{\rho\bar{V}^2}{2}\left[k_i + k_o + \frac{f_{app}L}{D}\right] \tag{7}$$

The intake loss coefficient is k_i, while the output loss coefficient is k_o, then eq. (5) and (7) can be combined, as:

$$\Delta\rho_{tot} = \frac{k_i\rho\bar{V}^2}{2} + \frac{k_o\rho\bar{V}^2}{2} + \frac{2\left(f_{\mathrm{Re}}\right)\mu\bar{V}L}{D_h^2} + \frac{k(x)\rho\bar{V}^2}{2} \tag{8}$$

Ngo *et al.* [45] conducted computational and experimental on pressure drop in the microchannel heat exchanger with an S-shaped fin. Fuerstman *et al.* [46] experimented on pressure drop in a long microchannel with a rectangular cross-section using water and mixtures water and glycerol for working fluid. They concluded that the main contributor per unit length to the pressure drop along of microchannel that loads bubbles is dependent on the concentration of surfactant in the liquid in which the bubbles move.

B. Heat transfer

On the channel inner surface with steady heat flux, the border circumstance has Nusselt number of fully developed laminar flows of 4.364. Zhang *et al.* [47] conduct a study on liquid flow and heat transfer in the rough microchannel. Klein *et al.* [48] analyzed water flow with alkyl polyglycoside surfactant APG in 26 triangular parallel micro canals with a hydraulic diameter of 108 μm to gained prime solvent concentration and mass flux for increasing heat transfer. Lee *et al.* [49] conducted experimental and numerical on deionized water in the copper rectangular microchannel with hydraulic diameter from 323 - 1068 μm in Reynolds number range of 300 – 3500 to obtain predicted heat transfer applications in the microchannel. They showed that experimental data accord with the numerical result, but mismatch with the conventional channel correlation. Li *et al.* [50] studied numerical and experimental flow and heat transfer characteristic of deionized water in microchannel made from silica and stainless with a hydraulic diameter of 50-1570 μm in the Reynolds number range from 20 to 2400. They showed that in the hydraulic diameter < 50 μm silica channel the water flow behavior agrees with macro-scale channel and increases of the Reynolds number affected the heat transfer. Lee and Garimella [51] presented a research project of saturated flow heat transfer and pressure drop of deionized water in the silicon rectangular microchannel with a hydraulic diameter range from 162 to 571 μm. They presented the effect of pressure drop and heat transfer as a function of applied heat flux. Dai *et al.* [52] studied experimentally water flow in tortuous microgroove with a semi-circular cross-section in the range of 50 to 900 Reynolds numbers. They concluded that flow in zig-zag microchannel configuration increased heat transfer rate of effect geometrical parameter. Xu *et al.* [1] reported they experimentally and numerically study on micro air cooler U– shape for a CPU cooler with rectangular pin fin which has high thermal conductivity and decreases air flow rate.

C. Flow structure and pressure drop in miter bend microchannel

Taassob *et al.* [53] numerically explored the impact of sharp bends and curved corners on rarefied gas flow in the microchannel to obtain thermal and hydrothermal behaviors. They reported that a rise in in corner radius results in a rise in mass flow rate. Besides that applying curvature as a substitute for sharp turns increase the average shear stress and slip velocity. Aoki *et al.* [4] studied experimentally bend geometry and confluence in the micromixing. They demonstrated that the mixing feat will be better by combining the confluence and bend channel also the mixing speed is increased by the addition of the confluence angle. Furthermore, the pressure drop produced is equivalent to the channel with or without the bend.

Al-Neama *et al.* [54] conducted both experimentally and numerically investigation on four type configuration design of a rectangular copper microchannel heat sink to obtain the effect of single-phase liquid flow. Its type configuration is straight microchannel, single serpentine, double serpentine and triple serpentine microchannel. They reported the single route serpentine microchannel

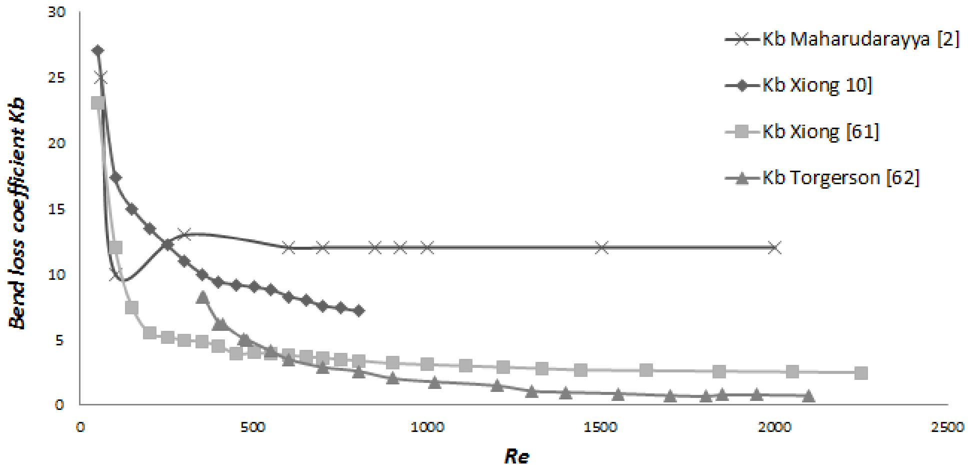

Figure 1. Bend loss coefficient vs Reynolds number

design presents the most potent heat transfer but also the greatest pressure drop [55]. White *et al.* [56] conducted numerical studies on the gas flow with varying degrees of rarefaction in a microchannel with 90° bends. That's studies with direct simulation Monte Carlo. They reported that choosing the right mesh size for the corner area is important so that the shaft and size of the recirculation zone are visible.

Rovenskaya [57] conducted the same kind of studies however they used the Navier-Stoks equation for flow rate and Poiseuille number. Nguyen *et al.* [58] Experimentally investigated water flow in a rectangular xerographic microchannel with a ratio of cross-sectional area of 0.2, 0.33, and 0.5 was tested experimentally in the ranges of 150 to 3200 Reynolds numbers to obtain minor losses for 90° bends. They reported that the coefficient of minor loses depending on Reynolds number and area ratio of contraction and expansion in bend.

Arun *et al.* [59] numerically and experimentally studied flow characteristics of single-phase fluid following through sharp and miter segment 90° bends microchannel sink computational fluid dynamics. They reported that pressure drop of sharp bends higher 307 % than mitered segment bends. Which has been done two-dimensional gas flow simulation by Agrawal *et al.* [60]. Xiong and Chung [10][61] studied flow characteristics and pressure drop in microchannels with hydraulic diameters of 209, 412, and 622 µm of pressure-driven are serpentine rectangular microchannels between 100 and 1700 in the Reynolds number range. They demonstrated that during the Reynolds number transition at 1500-1700, on the Re <100 the vortices not occurred in the bends wall and on the Re > 100 to 1000 the vortices occurred in the constant sharp and size.

Torgerson *et al.* [62] studied experimentally fluid flow in a rectangular xerographic microchannel in the Reynolds number range of 250- 4000 with a channel aspect ratio of 0.45-0.074. They showed that in the critical Re range of 1800 to 2300, the loss coefficient in bend increases when Reynolds number <1200 and decreases significantly when Re above that's. Maharudrayya *et al.* [2] reported a numerical study on laminar fluid flow in fuel cell microchannel with 1800 bends to investigated pressure drop characteristics and obtained bend loss coefficient. They showed that on the Reynolds number > 1000 bend loss is the major part of the total pressure loss.

The bend loss coefficient was shown as a function of Reynolds number in Figure 1. Where Maharudrayya *et al.* [2] and Xiong and Chung [10], using the CFD simulation method while Xiong and Chung [61] and Torgerson *et al.* [62] using the experimental method. The simulation findings reveal that they do not match the experimental data, whereas Xiong and Chung [61], and Torgerson *et al.* [62] experimental results demonstrate the agreement. This study's results may differ due to variances in cross-sectional form and material of microchannel.

IV. Conclusion

This research is discussing a topic of the characteristics of single-phase fluid flow in microchannels with bends. The possible conclusion be drawn from the available data is that the fluid which flow with a low Reynolds number under 100 does not affect the pressure drop, but on the Reynolds number above that the pressure drop has been increased as the appears of vortices in the outer and inner walls around the channel bends causes an increase in the additional pressure drop. Whereas at Reynolds number above 1000 the bend loss coefficient (Kb) almost remains constant and has fluctuated in the range of ±10 %. The other finding shows that the reduction in diameter bend tube can increase the pressure drop. At further research, it is recommended to studies the properties of liquid flow on the microchannel which is influenced by the presence of the variety of bends angles and a wider range of Reynolds numbers, especially to obtain minor loss effect accurately.

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Declarations

Author contribution

Endro Junianto is the main contributor of this paper. All authors read and approved the final paper.

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Conflict of interest

The authors declare no known conflict of financial interest or personal relationships that could have appeared to influence the work reported in this paper.

Additional information

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