

# 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 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  $K_b$  almost remains constant and change in the range of  $\pm 10\%$ . 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 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  $\mu m$  and 357  $\mu m$  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  $\mu m$  for Reynolds number

ranges through 150 to 2800. The essential Reynolds number for a conduit with an inner diameter of 400  $\mu\text{m}$  was calculated to be around 1500, and the friction factor effect was increased during the surface roughness escalation. Toghräie *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  $\mu\text{m}$  height, and 250  $\mu\text{m}$  width using R134a as the working fluid. They demonstrate that, as the surface roughness increase from 2.03  $\mu\text{m}$  – 15.86  $\mu\text{m}$ , the heat transfer coefficient was increased up to 45 %.

Some studies conducted a numerical 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 the influence of surface roughness on laminar fluid flow in an annular microchannel. Zaghiani and Kosar [24] investigated numerically an effect of pin fin shape and surface roughness on heat transfer and mass 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:

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

Canal aspect ratio,  $\alpha$  is determined as:

$$\alpha = \frac{a}{b} \quad (2)$$

When the term "laminar theory" is used to describe a common observation of differences.

$$C^* = \frac{(fRe)_{\text{experimental}}}{(fRe)_{\text{theoretical}}} \quad (3)$$

Where  $fRe$  denotes the non-dimensionalized representation that experimentally and theoretically projected 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  $\mu\text{m}$  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  $\mu\text{m}$  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 friction 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  $\alpha$  vs a function of the microchannel aspect ratio  $\gamma$  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  $\mu\text{m}$  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 a microchannel with a diameter from 146.7–203  $\mu\text{m}$ . 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 friction factor turbulent stream gas in rectangular microchannel made silicon and capped glass with a hydraulic diameter of 99.36 and 146.76  $\mu\text{m}$ . 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,  $f_{\text{exp}}$  was decided using the pressure difference as follows:

$$f_{\text{exp}} = \frac{2\Delta P D_h}{\rho V^2 L} \quad (4)$$

where  $\Delta P$  is the pressure difference,  $L$  is the length device, and  $V$  is the mean velocity determined from the mass flow rate.

The theoretical Poiseuille number,  $Po = fRe$ , is constant for laminar flow and is a function of  $\alpha$  for rectangular cross-section channels.

Shen *et al.* [27] experimental investigation of deionized water flow in 26 rectangular microchannels with a width of 300  $\mu\text{m}$  and a depth of 800  $\mu\text{m}$ , it flowed in the Reynolds number ranging from 162 to 1257 and temperatures inlet of 30, 50, and 70  $^{\circ}\text{C}$ . They declared that higher inlet deionized water temperature can give better relatively flow performance, and when the predicted friction factor value was high 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  $\mu\text{m}$  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 100–1000 Reynolds number range. On the rectangular channel, the friction factor and Reynolds number effect appear to be large, according to them. Park and Punch [37] conducted an experimental investigation on friction factor in the rectangular microchannels with hydraulic diameters ranging from 106 to 347  $\mu\text{m}$  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 theory. [43] *et al.* [38] tested friction factors in a triangular and rectangular microchannel with hydraulic diameters of 400 and 600  $\mu\text{m}$ , respectively, using R12 and R134a as working fluids. 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. Result and Discussion

#### A. Pressure Drop

Pfund *et al.* [39] measured friction and pressure drop in a rectangular microchannel with a depth range from 128 to 521  $\mu\text{m}$  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 roughness 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  $\mu\text{m}$  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 390, but on two-phase flow increased the pressure drop with 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. Q [24] *et al.* [42] conducted computational and experimental studies on the water flow and pressure drop in the rectangular microchannel with 222  $\mu\text{m}$  of width, 694

$\mu\text{m}$  of depth and 120 mm with range of Reynolds numbers from 196 – 2215. They show that the suitability [16] 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  $\mu\text{m}$  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:

$$\Delta p = \frac{2(f_{Re})\mu\bar{V}L}{D_h^2} + \frac{\kappa(x)\rho\bar{V}^2}{2} \quad (5)$$

Where  $\kappa$  is the Hagenbach factor, determined by:

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

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

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

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

31

Table 1.

Selected literature for single-phase flow in microchannel

Author	Year	Fluid/ Form	Form	$D_h$ ( $\mu\text{m}$ )	$\alpha \approx a/b$	$Re$	$C^*$	$f_{Re}$	$L/D_h$	Remarks
Pfund <i>et al.</i> [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 <i>et al.</i> [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 56 angular channels, predictions 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 <i>et al.</i> [34]	2006	Water/ Liquid	R	436	2.67	162– 1257	1– 2.84	-	16–754	In rough microchannels, surface roughness has a partial 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 <i>et al.</i> [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	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 <i>et al.</i> [18]	2016	Water/ liquid	C	400	-	150– 2800	-	-	25	The friction factor increase when surface roughness increased
Jafari <i>et al.</i> [1]	2016	R134a	R	368	2.8	15.8– 36.8	-	-	52	Heat transfer experiment increase 45%

C: circular; R: rectangular; T: trapezoid

$$\Delta p_{tot} = \frac{k_f \rho \bar{V}^2}{2} + \frac{k_v \rho \bar{V}^2}{2} + \frac{2(f_{Re}) \mu \bar{V} L}{D_h^2} + \frac{k(x) \rho \bar{V}^2}{2} \quad (8)$$

Ngo *et al.* [62] conducted computational and experimental on pressure drop in the microchannel heat exchanger with an S-shaped. Fuerstman *et al.* [46] experimented on pressure drop in a long microchannel with a rectangular cross-section using water and mixture of 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 circumference has a Nusselt number of 4,364 completely developed laminar flow.

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 diameter of 108  $\mu\text{m}$  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  $\mu\text{m}$  in Reynolds number range of 24 - 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  $\mu\text{m}$  in the Reynolds number range from 20 to 2400. They showed that in the hydraulic diameter < 50  $\mu\text{m}$  silica channel the water flow behavior agrees with macro-scale channel and increases of the Reynolds number affected the heat transfer. Lee and Gnanella [51] presented a research project of saturated flow pressure drop of deionized water in the silicon rectangular microchannel with a hydraulic diameter range from 162 to 571  $\mu\text{m}$ . They presented the effect of pressure drop. Dai *et al.* [52] researched the hydrodynamic flow through a 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 hydrothermal behaviors. They reported that a rise in corner radius results in a rise in mass flow rate. Besides that, varying 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 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-Stokes equation for flow rate and Poiseuille number. Nguyen *et al.* [58] 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 losses depending on Reynolds number and the area ratio of contraction and expansion in bends.



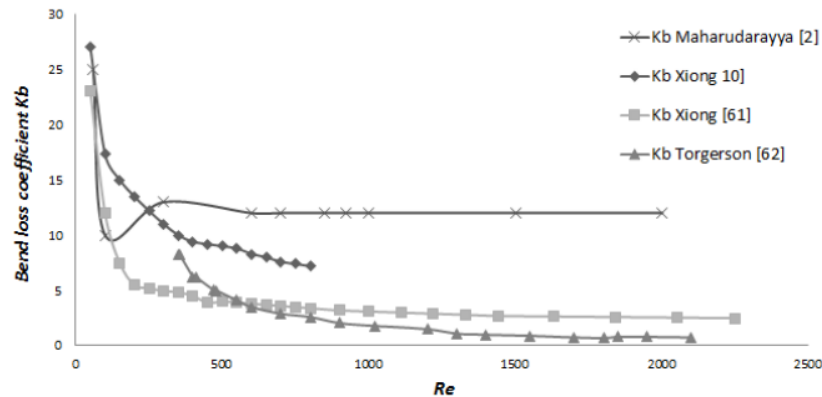


Figure 1. Bend loss coefficient vs Reynolds number

Arun *et al.* [59] investigated flow properties numerically and empirically 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  $\mu\text{m}$  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  $\text{Re} < 100$  the vortices not occurred in the bends wall and on the  $\text{Re} > 100$  to 1000 the vortices occurred in the constant sharp bend size. Torgerson *et al.* [62] studied experimentally fluid flow in a rectangular xerographic microchannel in the Reynolds number range of 250- 4000 with a 0,45-0,074 channel aspect ratio. 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 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 given data is that the fluid which flows 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 a Reynolds number above 1000 the bend loss coefficient ( $K_b$ ) almost remains constant and has fluctuated in the range of  $\pm 10\%$ . 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.

#### References

- [1] Y. Xu, H. Fan, and B. Shao, "Experimental and numerical investigations on heat transfer and fluid flow characteristics of integrated U-shape micro heat pipe array with rectangular pin fins," *Appl. Therm. Eng.*, vol. 168, p. 114640, 2020.
- [2] S. Maharudrayya, S. Jayanti, and A. P. Deshpande, "Pressure losses in laminar flow through serpentine channels in fuel cell stacks," *J. Power Sources*, vol. 138, no. 1-2, pp. 1-13, 2004.
- [3] T. Ouyang, J. Lu, Z. Zhao, J. Chen, and P. Xu, "New insight on the mechanism of vibration effects in vapor-feed microfluidic fuel cell," *Energy*, vol. 225, p. 120207, Jun. 2021.
- [4] N. Aoki, T. Fukuda, N. Maeda, and K. Mae, "Design of confluence and bend geometry for rapid mixing in microchannels," *Chem. Eng. J.*, vol. 227, pp. 198-202, 2013.
- [5] E. Mousset, "Unprecedented reactive electro-mixing reactor: Towards synergy between micro- and macro-reactors?," *Electrochem. commun.*, vol. 118, p. 106787, Sep. 2020.
- [6] R. Gatignol, "Asymptotic modelling of flows in microchannel by using Navier-Stokes or Burnett equations and comparison with DSMC simulations," *Vacuum*, vol. 86, no. 12, pp. 2014-2028, Jul. 2012.
- [7] A. Qazi Zade, A. Ahmadzadegan, and M. Renksizbulut, "A detailed comparison between Navier-Stokes and DSMC simulations of multicomponent gaseous flow in microchannels," *Int. J. Heat Mass Transf.*, vol. 55, no. 17-18, pp. 4673-4681, Aug. 2012.
- [8] J. Chen, S. K. Stefanov, L. Baldas, and S. Colin, "Analysis of flow induced by temperature fields in ratchet-like microchannels by Direct Simulation Monte Carlo," *Int. J. Heat Mass Transf.*, vol. 99, pp. 672-680, Aug. 2016.
- [9] A. Gavasane, A. Agrawal, and U. Bhandarkar, "Study of rarefied gas flows in backward facing micro-step using Direct Simulation Monte Carlo," *Vacuum*, vol. 155, pp. 249-259, Sep. 2018.
- [10] R. Xiong and J. N. Chung, "Effects of miter bend on pressure drop and flow structure in micro-fluidic channels," *Int. J. Heat Mass Transf.*, vol. 51, no. 11-12, pp. 2914-2924, 2008.
- [11] S. Buscher, "Two-phase pressure drop and void fraction in a cross-corrugated plate heat exchanger channel: Impact of flow direction and gas-liquid distribution," *Exp. Therm. Fluid Sci.*, vol. 126, p. 110380, Aug. 2021.
- [12] W. Bai, W. Chen, L. Yang, and M. K. Chyu, "Numerical investigation on heat transfer and pressure drop of pin-fin array under the influence of rib turbulators induced vortices," *Int. J. Heat Mass Transf.*, vol. 129, pp. 735-745, Feb. 2019.

- [13] A. I. Bashir, M. Everts, and J. P. Meyer, "Influence of inlet contraction ratios on the heat transfer and pressure drop characteristics of single-phase flow in smooth circular tubes in the transitional flow regime," *Exp. Therm. Fluid Sci.*, vol. 109, p. 109892, Dec. 2019.
- [14] H. Fazelnia, S. Azarhazin, B. Sajadi, M. A. A. Behabadi, S. Zakeralhosseini, and M. V. Rafeinejad, "Two-phase R1234yf flow inside horizontal smooth circular tubes: Heat transfer, pressure drop, and flow pattern," *Int. J. Multiph. Flow*, vol. 140, p. 103668, Jul. 2021.
- [15] I. Papautsky, T. Ameel, and A. B. Frazier, "A review of laminar single-phase flow in microchannels," in *ASME, Proceedings of Int. Mech. Eng Congress Expos Proc (IMECE)*, 2001, vol. 2, pp. 3067–3075.
- [16] M. H. Mousa, N. Miljkovic, and K. Nawaz, "Review of heat transfer enhancement techniques for single phase flows," *Renew. Sustain. Energy Rev.*, vol. 137, p. 110566, Mar. 2021.
- [17] S. G. Kandlikar, S. Joshi, and S. Tian, "Effect of channel roughness on heat transfer and fluid flow characteristics at low Reynolds numbers in small diameter tubes," *Atmosphere (Basel)*, vol. 4, no. 7, 2001.
- [18] X. Yuan, Z. Tao, H. Li, and Y. Tian, "Experimental investigation of surface roughness effects on flow behavior and heat transfer characteristics for circular microchannels," *Chinese J. Aeronaut.*, vol. 29, no. 6, pp. 1575–1581, 2016.
- [19] D. Toghaie, R. Mashayekhi, M. Niknejadi, and H. Arasteh, "Hydrothermal performance analysis of various surface roughness configurations in trapezoidal microchannels at slip flow regime," *Chinese J. Chem. Eng.*, 2020.
- [20] R. Jafari, T. Okutucu-Ozyurt, H. Ö. Ünver, and Ö. Bayer, "Experimental investigation of surface roughness effects on the flow boiling of R134a in microchannels," *Exp. Therm. Fluid Sci.*, vol. 79, pp. 222–230, 2016.
- [21] L. Guo, H. Xu, and L. Gong, "Influence of wall roughness models on fluid flow and heat transfer in microchannels," *Appl. Therm. Eng.*, vol. 84, pp. 399–408, 2015.
- [22] J. R. Valdés, M. J. Miana, J. L. Pelegay, J. L. Núñez, and T. Pütz, "Numerical investigation of the influence of roughness on the laminar incompressible fluid flow through annular microchannels," *Int. J. Heat Mass Transf.*, vol. 50, no. 9–10, pp. 1865–1878, 2007.
- [23] J. R. Valdés, M. J. Miana, M. Martínez, L. Gracia, and T. Pütz, "Introduction of a length correction factor for the calculation of laminar flow through microchannels with high surface roughness," *Int. J. Heat Mass Transf.*, vol. 51, no. 17–18, pp. 4573–4582, 2008.
- [24] A. K. Sadaghiani and A. Kosar, "Numerical investigations on the effect of fin shape and surface roughness on hydrothermal characteristics of slip flows in microchannels with pin fins," *Int. J. Therm. Sci.*, vol. 124, pp. 375–386, 2018.
- [25] H. Lu, M. Xu, L. Gong, X. Duan, and J. C. Chai, "Effects of surface roughness in microchannel with passive heat transfer enhancement structures," *Int. J. Heat Mass Transf.*, vol. 148, p. 119070, 2020.
- [26] J. Judy, D. Maynes, and B. W. Webb, "Characterization of frictional pressure drop for liquid flows through microchannels," *Int. J. Heat Mass Transf.*, vol. 45, no. 17, pp. 3477–3489, 2002.
- [27] H. Y. Wu and P. Cheng, "Friction factors in smooth trapezoidal silicon microchannels with different aspect ratios," *Int. J. Heat Mass Transf.*, vol. 46, no. 14, pp. 2519–2525, 2003.
- [28] G. L. Morini, M. Spiga, and P. Tartarini, "The rarefaction effect on the friction factor of gas flow in microchannels," *Superlattices Microstruct.*, vol. 35, no. 3–6, pp. 587–599, 2004.
- [29] V. Silvério and A. L. N. Moreira, "Friction losses and heat transfer in laminar microchannel single-phase liquid flow, 6th Int," 2008.
- [30] Z.-X. Li, D. X. Du, and Z.-Y. Guo, "Characteristics of frictional resistance for gas flow in microtubes," in *Proceedings of symposium on energy engineering in the 21st Century*, 2000, vol. 2, pp. 658–664.
- [31] C. Hong, T. Nakamura, Y. Asako, and I. Ueno, "Semi-local friction factor of turbulent gas flow through rectangular microchannels," *Int. J. Heat Mass Transf.*, vol. 98, pp. 643–649, 2016.
- [32] C. Hong, T. Shigeishi, Y. Asako, and M. Faghri, "Experimental investigations of local friction factors of laminar and turbulent gas flows in smooth micro-tubes," *Int. J. Heat Mass Transf.*, vol. 158, p. 120035, Sep. 2020.
- [33] C. Hong, T. Nakamura, Y. Asako, and I. Ueno, "Semi-local friction factor of turbulent gas flow through rectangular microchannels," *Int. J. Heat Mass Transf.*, vol. 98, pp. 643–649, Jul. 2016.
- [34] S. Shen, J. L. Xu, J. J. Zhou, and Y. Chen, "Flow and heat transfer in microchannels with rough wall surface," *Energy Convers. Manag.*, vol. 47, no. 11–12, pp. 1311–1325, 2006.
- [35] G. P. Celata, G. L. Morini, V. Marconi, S. J. McPhail, and G. Zummo, "Using viscous heating to determine the friction factor in microchannels—An experimental validation," *Exp. Therm. Fluid Sci.*, vol. 30, no. 8, pp. 725–731, 2006.
- [36] P. Gunasegaran, H. Mohammed, and N. H. Shuaib, "Pressure drop and friction factor for different shapes of microchannels," in *2009 3rd International Conference on Energy and Environment (ICEE)*, 2009, pp. 418–426.
- [37] H. S. Park and J. Punch, "Friction factor and heat transfer in multiple microchannels with uniform flow distribution," *Int. J. Heat Mass Transf.*, vol. 51, no. 17–18, pp. 4535–4543, 2008.
- [38] L. S. Ding, H. Sun, X. L. Sheng, and B. D. Lee, "Measurement of friction factors for R134a & R12 through microchannel," 2000, Accessed: Jul. 26, 2021. [Online].
- [39] D. Pfund, D. Rector, A. Shekariz, A. Popescu, and J. Welty, "Pressure drop measurements in a microchannel," *AIChE J.*, vol. 46, no. 8, pp. 1496–1507, 2000.
- [40] M. Bahrami, M. M. Yovanovich, and J. R. Culham, "Pressure Drop of Fully-Developed, Laminar Flow in Microchannels of Arbitrary Cross-Section," *J. Fluids Eng.*, vol. 128, no. 5, pp. 1036–1044, Sep. 2006.
- [41] Y. W. Hwang and M. S. Kim, "The pressure drop in microtubes and the correlation development," *Int. J. Heat Mass Transf.*, vol. 49, no. 11–12, pp. 1804–1812, 2006.
- [42] W. Qu, I. Mudawar, S.-Y. Lee, and S. T. Wereley, "Experimental and computational investigation of flow development and pressure drop in a rectangular micro-channel," 2006.
- [43] P. Hrnjak and X. Tu, "Single phase pressure drop in microchannels," *Int. J. Heat Fluid Flow*, vol. 28, no. 1, pp. 2–14, 2007.
- [44] M. E. Steinke and S. G. Kandlikar, "Single-phase liquid friction factors in microchannels," *Int. J. Therm. Sci.*, vol. 45, no. 11, pp. 1073–1083, 2006.
- [45] T. L. Ngo, Y. Kato, K. Nikitin, and T. Ishizuka, "Heat transfer and pressure drop correlations of microchannel heat exchangers with S-shaped and zigzag fins for carbon dioxide cycles," *Exp. Therm. Fluid Sci.*, vol. 32, no. 2, pp. 560–570, 2007.
- [46] M. J. Fuerstman, A. Lai, M. E. Thurlow, S. S. Shevkoplyas, H. A. Stone, and G. M. Whitesides, "The pressure drop along rectangular microchannels containing bubbles," *Lab Chip*, vol. 7, no. 11, pp. 1479–1489, 2007.
- [47] X. Zhang, T. Zhao, S. Wu, and F. Yao, "Experimental Study on Liquid Flow and Heat Transfer in Rough Microchannels," *Adv. Condens. Matter Phys.*, vol. 2019, pp. 1–9, Nov. 2019.
- [48] D. Klein, G. Hetsroni, and A. Mosyak, "Heat transfer characteristics of water and APG surfactant solution in a micro-channel heat sink," *Int. J. Multiph. Flow*, vol. 31, no. 4, pp. 393–415, 2005.
- [49] P.-S. Lee, S. V. Garimella, and D. Liu, "Investigation of heat transfer in rectangular microchannels," *Int. J. Heat Mass Transf.*, vol. 48, no. 9, pp. 1688–1704, 2005.
- [50] Z. Li, Y.-L. He, G.-H. Tang, and W.-Q. Tao, "Experimental and numerical studies of liquid flow and heat transfer in microtubes," *Int. J. Heat Mass Transf.*, vol. 50, no. 17–18, pp. 3447–3460, 2007.
- [51] P.-S. Lee and S. V. Garimella, "Saturated flow boiling heat transfer and pressure drop in silicon microchannel arrays," *Int. J. Heat Mass Transf.*, vol. 51, no. 3–4, pp. 789–806, 2008.
- [52] Z. Dai, D. F. Fletcher, and B. S. Haynes, "Impact of tortuous geometry on laminar flow heat transfer in microchannels," *Int. J. Heat Mass Transf.*, vol. 83, pp. 382–398, 2015.
- [53] A. Taassob, R. Kamali, and A. Bordbar, "Investigation of rarefied gas flow through bended microchannels," *Vacuum*, vol. 151, pp. 197–204, 2018.
- [54] A. F. Al-Neama, N. Kapur, J. Summers, and H. M. Thompson, "An experimental and numerical investigation of the use of liquid flow in serpentine microchannels for microelectronics cooling," *Appl. Therm. Eng.*, vol. 116, pp. 709–723, 2017.
- [55] M. A. Ansari and K.-Y. Kim, "Parametric study on mixing of two fluids in a three-dimensional serpentine microchannel," *Chem. Eng. J.*, vol. 146, no. 3, pp. 439–448, Feb. 2009.
- [56] C. White, M. K. Borg, T. J. Scanlon, and J. M. Reese, "A DSMC investigation of gas flows in micro-channels with bends," *Comput. Fluids*, vol. 71, pp. 261–271, 2013.
- [57] O. I. Rovenskaya, "Computational study of 3D rarefied gas flow in microchannel with 90 bend," *Eur. J. Mech.*, vol. 59, pp. 7–17, 2016.
- [58] L. Nguyen, J. Elsnab, and T. Ameel, "Contraction/expansion effects in 90 miter bends in rectangular xurographic microchannels," in *ASME 2011 9th International Conference on Nanochannels, Microchannels, and Minichannels*, 2011, pp. 667–677.
- [59] G. Arun, S. P. K. Babu, S. Natarajan, and N. Kulasekharan, "Study of flow behaviour in sharp and mitred pipe bends," *Mater. Today Proc.*, 2019.
- [60] A. Agrawal, L. Djenidi, and A. Agrawal, "Simulation of gas flow in microchannels with a single 90 bend," *Comput. Fluids*, vol. 38, no. 8, pp. 1629–1637, 2009.
- [61] R. Xiong and J. N. Chung, "Flow characteristics of water in straight and serpentine micro-channels with miter bends," *Exp. Therm. Fluid Sci.*, vol. 31, no. 7, pp. 805–812, 2007.

[62] D. Torgerson, R. Kolekar, B. Gale, and T. Ameel, "Minor losses in rectangular xurographic microchannels," in *ASME 2010 International*

*Mechanical Engineering Congress and Exposition*, 2010, pp. 453–462.



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C. S. Chen. "Reduced Navier-Stokes Simulation of Incompressible Microchannel Flows", Numerical Heat Transfer, Part A: Applications, 2007

Crossref

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11

Mirmanto(Karayiannis, TG, Kenning, DBR and Lewis, JS). "Single-phase flow and flow boiling of water in horizontal rectangular microchannels", Brunel University School of Engineering and Design PhD Theses, 2013.

Publications

21 words — 1%

12

Nguyen, Lam, John Elsnab, and Tim Ameen. "Contraction/Expansion Effects in 90° Miter Bends in Rectangular Xurographic Microchannels", ASME 2011 9th International Conference on Nanochannels Microchannels and Minichannels Volume 1, 2011.

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Xiong, R.. "Flow characteristics of water in straight and serpentine micro-channels with miter bends", Experimental Thermal and Fluid Science, 200707

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- 
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- 
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Crossref

10 words — < 1%

36 Vimal Kumar, Marius Paraschivoiu, K.D.P. Nigam. "Single-phase fluid flow and mixing in microchannels", Chemical Engineering Science, 2011

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41 Ergu, O.B.. "Pressure drop and point mass transfer in a rectangular microchannel", International Communications in Heat and Mass Transfer, 200907

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42 G. L. Morini, M. Lorenzini, S. Salvigni, G. P. Celata. "Experimental Analysis of Microconvective Heat

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## Transfer in the Laminar and Transitional Regions", Experimental Heat Transfer, 2009

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- 
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- 
- 48 Amirah M. Sahar, Jan Wissink, Mohamed M. Mahmoud, Tassos G. Karayiannis, Mohamad S. Ashrul Ishak. "Effect of hydraulic diameter and aspect ratio on single phase flow and heat transfer in a rectangular microchannel", Applied Thermal Engineering, 2017  
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- 
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- 
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- 
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- 
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- 62 J. M. Yin, C. W. Bullard, P. S. Hrnjak. "Single-Phase Pressure Drop Measurements in a Microchannel Heat Exchanger", Heat Transfer Engineering, 2002 6 words — < 1%  
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- 
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