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Flow and heat transfer for gas flowing in microchannels: a review

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Abstract Microchannels are currently being used in many areas and have high potential for applications in many other areas, which are considered realistic by experts. The application areas include medicine, biotechnology, avionics, consumer electronics, telecommunications, metrology, computer technology, office equipment and home appliances, safety technology, process engineering, robotics, automotive engineering and environmental protection. A number of these applications are introduced in this paper, followed by a critical review of the works on the flow and heat transfer for gas flowing in microchannels. The results show that the flow and heat transfer characteristics of a gas flowing in microchannels can not be adequately predicted by the theories and correlations developed for conventional sized channels. The results of theoretical and experimental works are discussed and summarized along with suggestions for future research directions.

1
Introduction

Miniaturization of devices has become a focus of interest to industry and has evolved into an important field of research in the past decade. Phrases such as microelectromechanical systems (MEMS), micro system technologies (MST), and Mechatronics have been used in the US, Europe and Japan, respectively to describe the design, development and manufacturing processes of very small scale (submicron to millimeter) devices and systems.

Major industrial countries have recognized the significance of MEMS and MST and have implemented programs to support and coordinate activities related to this technology. The number of companies and institutes working on MEMS technology in 1991 was about 300 worldwide. This number has grown rapidly to about 8000 in 1995 as many academic and research institutes have joined the MEMS and MST related activities [1].

A number of market studies have been performed on the future of micro system technologies, the latest of which performed by NEXUS [2] contains in depth analysis of MST market through the year 2002. According to this report, the total world market for microsystems is expected to grow from $14 billion in 1996 to $38 billion in 2002. The report provides growth estimate for the products currently available in the market as well as the developmental products that have high probability of being on the market by 2002.

Microsystems are currently being used in many areas and have high potential for applications in many other areas which are considered realistic by experts. The application areas include medicine, biotechnology, avionics, consumer electronics, telecommunications, metrology, computer technology, office equipment and home appliances, safety technology, process engineering, robotics, automotive engineering and environmental protection. Devices such as hard disk drive heads, inkjet printheads, heart pacemakers, pressure and chemical sensors, drug delivery systems, infrared imagers, micromotors, microchannel reactors, micropumps and turbines, and microchannel heat sinks are just a few among the large number of microdevices being commercially used or will be used in the near future.

Many miniaturized devices involve the flow of a fluid in microchannels and may also be combined with heat transfer and chemical reaction. A number of these microfluidic devices are described in this paper. Further, this paper intends to review the recent experimental and theoretical work dealing with flow and heat transfer for gas flow in microchannels only.

Depending on the research objectives and the methods used, the work published on the thermo-fluid aspects of microchannels may be categorized as following:

(1) General applications: Applications of microfluidic systems and microchannels in various technological areas.
(2) Gas flow: Experimental studies as well as physical and numerical modeling of flow and heat transfer for a gas flowing in microchannels.
(3) Microchannel heat exchangers: Experimental and theoretical analysis on the overall performance of microchannel heat exchangers as an effective means of

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cooling for electronic components and compact chemical reactor.
(4) Liquid flow: Measurement and numerical modeling of heat transfer and pressure drop characteristics of liquids flowing in microchannels.
(5) Two-phase: Modeling of vapor dynamics and boiling characteristics of liquids flowing in microchannels, condensation and thermal performance of micro heat pipes.

In order to be more comprehensive in a reasonable length of paper, only items 1 and 2 will be reviewed here. The rest will be dealt with separately.

2
Microfluidic devices

A micro-pump is one example of a microfluidic system. Handling small amounts of fluids is a basic task in many fields of applications (chemical analysis, biotechnology, environmental monitoring, medical diagnostics, micro-dosing systems, dosage of lubrication oil, etc). With a volumetric flow rate of 10^{-12} to 10^{-8} m^3/s, micropumps can be used in many biofluidic, drug delivery, mixing and flow control applications.

Most of the micropump systems are valveless and are actuated by a vibrating membrane. In one of the designs [3], the pump consists of a silicon chip mounted on top of a plastic base plate and an actuator. The base plate contains the fluid adapter and the silicon chip contains an amplifying diaphragm, which is driven by the piezo actuator. By applying a DC voltage, the device operates in its valve mode. Fluid flow is made possible or blocked by altering the polarity of the driving voltage (voltage > 0: open; voltage < 0: closed). By applying a square wave voltage, the device operates in its pump mode. The direction of fluid transport can be changed by the driving frequency (bi-directional pump effect). The pump flow rate can be controlled by varying the driving frequency.

Sen et al. [4] proposed a micropump design which works based on a rotating cylinder in a microchannel. In this design, the cylinder, which is located axisymmetrically in a microchannel, rotates at a prescribed angular speed and propels the fluid due to the viscous action. As a bi-directional micropump, the flow direction can be reversed by changing the direction of rotation of the cylinder.

A microvalve is another microdevice which is mainly used for two purposes: (1) precise metering of very small flow rates that arise in biomedical and biochemical applications and (2) as a check valve for micro pumps. These valves are mainly used in automation technology, automotive industry and medical applications. The majority of micro-valves consist of a diaphragm that is actuated externally to open or close a flow port. In most of the earlier designs, the valves were single-orifice with micron-sized flow passage. As a result the flow in the passage is laminar (or Stokes), where viscous force plays the dominant role. Different designs use different method of actuation, such as magnetic, pneumatic, hydraulic or thermo-electric. In order to eliminate some of the drawbacks of a single valve, attempts have been made to use an array of valves so that a linear and more flexible control of the flow can be achieved [5, 6]. A search on the website of US Patent and Trademark Office has shown that 57 patents under the keyword “micro-valve were issued in the period 1998–1999.

Microchannel heat exchangers are microdevices, which have great potential applications in electronic cooling and chemical reactions. The performance of microchannel heat exchangers is quite remarkable. An exchanger in the form of a cube measuring 3 cm on a side can develop a heat transfer rate of 200 kW between hot and cold water with a flow rate of 7000 kg/h [7]. The improvement comes from the increased convection heat transfer coefficients in the small flow passages as well as a higher surface to volume ratio.

Several unique features of microchannel heat exchangers make them ideal for chemical applications. First of all, they have very short residence times (a few milliseconds), and heat up and cool-down rates on the order of 10000 K/min, which is suitable for fast reactions and compact reactors. Secondly, they have high safety feature due to low reactant inventory, which eliminates the accumulation of flammable gases. Thirdly, for heterogeneously catalyzed gas reactors, micro reactors offer the additional advantage of allowing for very large surface to volume ratio. Therefore, it should be possible to conduct heterogeneously catalyzed reactions involving a mixture of flammable gases in a micro reactor without any danger of open flames or explosions [8–12].

Safe operation of high density electronic components such as multichip modules and high power laser diodes, requires advanced cooling techniques and thermal management of these systems. In this regard, microchannel heat sinks have received considerable attention as a novel cooling device in the past decade. The pioneer work of Tuckerman and Pease [13–16] on high performance heat sinks has provoked numerous investigations on the use of microchannel heat sinks as means of cooling electronic components. An excellent review of the work done on microchannel heat sinks up to year 1992 is given by Goodling [17]. Shaukatullah [18] presented a bibliographic study of air cooled and liquid cooled heat sinks for thermal enhancement of electronic packages. According to these reports over one hundred thirty papers that were listed in this study were directly related to the application of microchannel heat sinks.

So far, we have mentioned some of the applications involving fluid flow and heat transfer in microchannels. Other applications have also been mentioned in the literature. Examples are micro-injectors [19], micromixers [20], and micronozzles [21]. These applications indicate that miniaturized flow passages of various geometry are either commonly used or have potential future applications. These geometries include plain or corrugated surface tubes, channels with different shapes of cross section, helical and other curved flow passages, orifices, flow contraction and expansion. The flow may be steady or unsteady; compressible or incompressible; Newtonian or non-Newtonian; laminar or turbulent; isothermal or non-isothermal. One may conclude that the entire area of fluid mechanics and convective heat transfer that are applied to conventional sized flow passages may indeed be relevant to the small flow passages as well.

3
Gas flow in microchannels

There are some effects that are usually neglected in the study of gas flow in macroscale, but have to be included in the analysis at microscale. One such effect is the non-continuum effect. Gas flow is typically classified as one of four regimes according to its Knudsen number [22]. The Knudsen number is defined as λ/H, where H is the characteristic lateral dimension of the channel and λ is the mean free path of gas molecules, defined by $\lambda = \mu\sqrt{\pi}/\sqrt{2\rho^2 RT}$, where μ is the absolute viscosity and R is the gas constant. These four flow regimes are as follows

Continuum flow	$\mathrm{Kn} < 10^{-3}$
Slip flow	$10^{-3} \le \mathrm{Kn} < 10^{-1}$
Transition flow	$10^{-1} \le \mathrm{Kn} < 10$
Free Molecular flow	$10 \le \mathrm{Kn}$

Gas flow in microchannels may involve other factors such as compressibility, rarefaction, and surface roughness effects.

Some of the experiments involve values of dimensionless numbers such as Mach number (M) and Knudsen number (Kn). The following relation is a useful tool to calculate Reynolds number (Re) from the specified values of M and Kn. This relation can be easily obtained from the definitions of M, Kn, Re, and the expression for the speed of sound for the ideal gas.

$$\mathrm{Re} = \sqrt{\frac{k\pi}{2}}\frac{\mathrm{M}}{\mathrm{Kn}} \tag{1}$$

where k is the specific heat ratio (c_p/c_v) for the gas. Since M and Kn usually vary along the flow channel due to heat transfer and/or compressibility effects, Re has to be considered variable too. Usually, choking must be avoided in order to have maximum flow rate at lowest pumping power, which means that M can not be greater than 1. For example, for air flow with $\mathrm{Kn} = 0.04$, the maximum value of local Re in the channel will be $\mathrm{Re}_{\max} = 35$.

We begin our review of the literature with the experimental work on the measurement of pressure drop and heat transfer coefficient of gas flow in microchannels. Wu and Little [23] measured friction factors experimentally for both laminar and turbulent gas flows in trapezoidal channels. The width of the channels was 130–200 μm and the depth was 30–60 μm. They observed friction factors larger than predicted by the established correlations, and a transition to turbulent flow at Reynolds number as low as 400. The silicon channels showed up to 60% deviation from the Moody chart, while the glass channels gave results that were 3–5 times those of the Moody chart. They attributed the large differences to the very high degree of surface roughness and to the uncertainty in the measurement of the dimensions of the channel. They compared the experimental data for the trapezoidal channels with correlations established for circular pipes. Wu and Little [24] also measured the heat transfer coefficients for nitrogen flow in microchannels with width in the range of 312 to 572 μm and from 89 to 97 μm deep. Their results were higher than prediction by the established correlations for Nusselt number. It was found that in the laminar range, the Nusselt number was a function of the Reynolds number and that the Reynolds analogy was not valid in the turbulent regime.

Choi et al. [25] measured the friction factor, inner wall surface roughness, and convective heat transfer coefficients for flow of nitrogen gas in microtubes for both laminar and turbulent flow regimes. The microtube inside diameters ranged from 3 to 81 μm and relative roughness from 0.00017 to 0.0116. The experimental results indicated significant departures from the standard correlations used for conventional-sized tubes. The measured value of $f * \mathrm{Re}$ for microtubes with a diameter less than 10 μm in the laminar range was 53 compared to the theoretical value of 64 for fully developed laminar flow in tubes. The results indicated that for microtubes with diameter less the 80 μm in the turbulent regime the Colburn analogy, $j_H = f/8$ was not valid. The Nusselt number in the turbulent flow was as much as 7 times that predicted by Colburn analogy. In the laminar regime, Nu exhibited a Reynolds number dependence, in contrast to the constant value predicted by theory. They also proposed correlations for the friction factor and the Nusselt number for the ranges of parameters involved in the experiments.

Pfahler et al. [26, 27] performed a series of experiments for measuring the friction factor and the apparent viscosity of fluids (gas and liquids) in microchannels ranging in depth from 0.5 to 40 μm. The gases used in the study were helium and nitrogen. The results for gases showed a reduction in C_f, as channel depth decreased for both gases. In the smallest channel studied, the data for gases showed that C_f decreased as Re decreased. Pong et al. [28] measured the pressure drop along rectangular microchannels for helium and nitrogen gas flow. The channels were from 5 to 40 μm wide, 1.2 μm deep and 3000 μm long. The pressure sensors were fabricated as an integral part of the flow channels. It was found that the pressure distribution was lower than that predicted by the continuum flow analysis and that it was not linear in the flow direction. The nonlinear effects were more pronounced for larger Knudsen number. In fact two factors work in opposite direction to shape the final pressure distribution. The compressibility effect causes the pressure to decrease more slowly. On the other hand, rarefaction effect caused by large values of Kn works against the compressibility and keeps the pressure toward the linear distribution. The two effects are not equal, resulting in a nonlinear pressure distribution. Liu et al. [29] used the same flow system described by Pong et al. [28] to obtain more experimental data on the pressure distribution in microchannels with uniform and non-uniform cross sectional areas. The uniform channel dimensions were 40 μm wide, 1.2 μm deep and 4.5 mm long. The pressure drop distribution was shown to be nonlinear. In the analysis performed by Liu et al. it was found that a steady, isothermal, and continuum flow with slip boundary condition accurately modeled the flow situation. However, the model could not explain the measured small pressure gradients near the inlet and the outlet.

Harley et al. [30] performed experimental and theoretical investigations of subsonic, compressible flow of nitrogen, helium and argon gases in long microchannels.

The channels were fabricated on silicon wafers and were typically 100 μm wide, 10 mm long and ranged in depth from 0.5 to 20 μm. The Knudsen number ranged from 0.001 to 0.4. Eight different trapezoidal channels were used with hydraulic diameter ranging from 1 to 36 μm. Most of the experimental data were presented in terms of the reduced Poiseuille number, $C^* = (\mathrm{Po})_{\mathrm{exp}}/(\mathrm{Po})_{\mathrm{theo}}$, where the Poiseuille number is $\mathrm{Po} = f * \mathrm{Re}$. $C^* = 1$ when the measured value of friction factor is equal to theoretical prediction. For the smallest channel (0.5 μm deep), C^* calculated using non-slip boundary conditions decreased from 0.98 to 0.82 as Re decreased from 0.43 to 0.012. Since Kn ranged from 0.004 to 0.373 for this case, which suggests transitional flow, the reduction in C^* was attributed to wall slip. The effect was pronounced at lower values of Re, which is due to higher values of Kn caused by larger mean free path due to lower pressure in the channel. Harley et al. [30] tried to examine whether wall slip can in fact describe the experimental observations. They included wall slip in their calculations, and were able to successfully predict the experimental data ($C^* \approx 1$). Figure 1 shows the experimental values of C^* as a function of Reynolds number for nitrogen, helium and argon gas flows in a 11.04 μm deep channel. C^* lies between 0.98 and 1.04, increasing with Re. Figure 2 shows the same results for a 0.51 μm deep channel. The Navier–Stokes equations with the conventional non slip boundary conditions (lower curve) overpredicts the pressure drop specially at low values of Re, corresponding to high values of Kn number (see Eq. (1)). Correcting for the slip velocity at the walls results in a better agreement of theory with the experimental data (upper curve in Fig. 2).

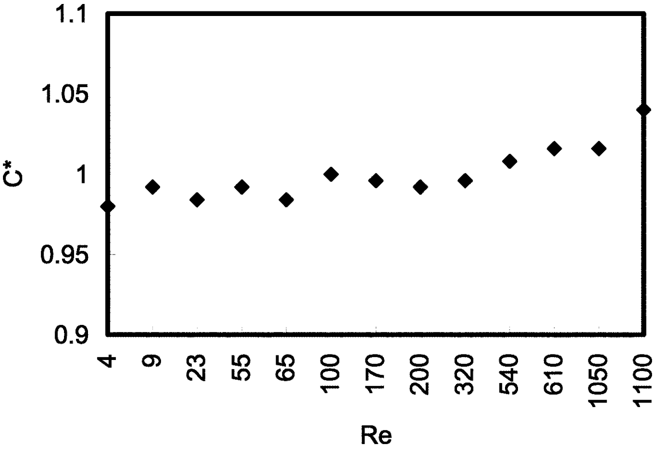

Fig. 1. C* as function of Re for nitrogen, helium and argon flow in 11.04 microns deep channel [30]

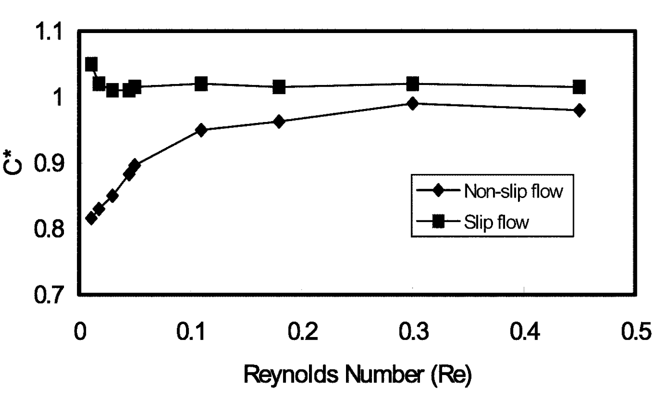

Fig. 2. C* as functions of Re for nitrogen and helium flow in a 0.51 micron deep channel [30]

Yu et al. [31] extended the work of Choi et al. [25] by conducting experimental and theoretical studies of flow and heat transfer in microtubes. Nitrogen gas and water were used in microtubes ranging in diameter from 12 to 102 μm. A range of Re between 250 and 20000 and Prandtl number from 0.7 to 5 were considered. The results for friction factor confirmed the findings of earlier investigators who noticed a lower value for the friction coefficient. The heat transfer coefficient was higher than that predicted by the standard correlations. The results were presented graphically and correlations were recommended for the calculation of friction factor and Nusselt number for the range of the parameters involved in the experiments.

Shih et al. [32] conducted experiments using a microchannel (40 μm wide, 1.2 μm deep, and 4000 μm long) to measure mass flow and axial pressure distribution for helium and nitrogen. Their results for helium gas were in reasonable agreement with the slip flow model, based on the first-order correction of the Navier–Stokes equations. The slip velocity at the wall is given by

$$u_{\mathrm{w}} = \sigma \mathrm{Kn}(\partial u/\partial y)_{\mathrm{w}} \qquad (2)$$

where σ is momentum accommodation coefficient and Kn is the Knudsen number. Historically, $\sigma = 1$ has been used for engineering calculations, although the experimental values vary between 1 and 1.5.

Figure 3 shows the mass flow rate in a microchannel as a function of the inlet pressure, while keeping the outlet pressure constant. Results of three theoretical models together with the experimental data of Shih et al. [23] are presented in the Figure. These models involve the solution of the N–S equations without slip flow correction, with 100% slip flow and 80% slip flow corrections. The 100% slip flow correction (solid line) results in a good agreement with the data, while the non-slip flow underpredicts and the 80% slip flow correction overpredicts the data. All models and as well as the experimental data show a non-linear dependence of the mass flow rate on the pressure drop.

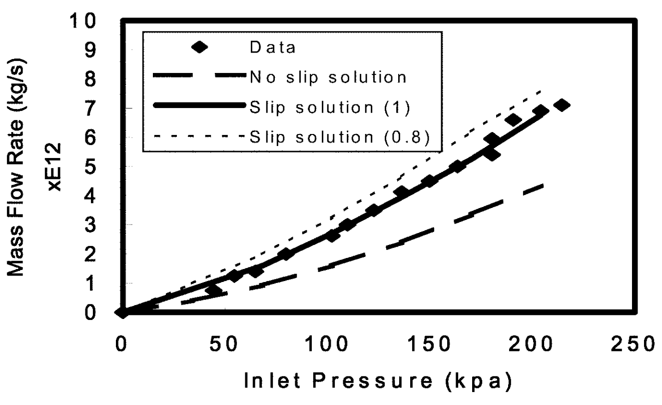

Fig. 3. Mass flow rate and pressure drop of helium in a microchannel [32]

More recently, Bayt and Breuer [33] performed experimental and numerical studies on the supersonic flow in micronozzles. The throat width of the 2-D nozzle ranged from 19 to 35 μm. Modeling was based on Navier–Stokes equations with non-slip boundary conditions. It was found that the nozzle efficiency compares well with the numerical model at high Reynolds numbers but deviates at low Reynolds number. The difference was attributed to the three dimensional effects.

Along with the experimental work, a number of researchers have utilized analytical or computational models to analyze gas flow in microchannels. These studies were aimed at predicting the experimental results and/or understanding the possible reasons behind the reduction in pressure drop and nonlinearity of the pressure distribution. Some of these works deal with compressibility effect, others look at the rarefaction effects, and still others are related to a fundamentally different approach to model gas flow in microchannels.

Beskok and Karniadakis [34] developed a numerical method to simulate time-dependent slip-flow of gases in complex microgeometries encountered in micro-devices such as micro-capillaries, micro-valves, and micro-bearings. Knudsen number was less than 0.1. Their method is based on the spectral element technique originally used to model incompressible flow by Navier–Stokes equations. The results of their model were compared with the experimental data for helium, already obtained by Pfahler [27]. For $\mathrm{Kn} = 0.044$, the slip-flow model predicted $C^* = 0.79$, while the experimental values were in the range of 0.80 to 0.85. They pointed out that the real mechanisms of momentum and heat transport in the micro-devices such as micro-capillaries, micro-valves, and microbearings are not well understood, and further validation of this technique was needed. Beskok et al. [35] extended their work to include compressibility and rarefaction effects in addition to using higher order slip boundary conditions.

Gaseous flow in 2-D microchannels with Cartesian geometry for various Knudsen numbers was studied by Harley et al. [30]. This investigation included analytical and experimental work on rarefied gas flow. The model assumed negligible wall normal pressure gradients and was based on the momentum equation in the flow direction with nonlinear terms neglected. The continuity equation was satisfied in an integral form and the velocity boundary conditions consisted of the first-order correction of nonzero wall velocity commonly used for slightly rarefied flows.

Arkilic et al. [36] developed a 2-D model for rarefied gas flow in microchannels by solving the Navier–Stokes equation subject to velocity slip boundary conditions. In this work, nonlinear terms were ignored, and the axial and tangential momentum as well as the differential continuity equations were satisfied. The channel was 52.25 μm wide, 1.33 μm deep, and 7500 μm long. The results showed that the pressure drop over the channel length was less than the continuum flow results, which is consistent with the experimental findings. An accommodation constant was introduced to represent the tangential momentum transfer between the impinging molecules and the wall. In order to demonstrate the relative contributions of compressibility and rarefied effects, Arkilic et al. [37] extended their work by incorporating the formal perturbation expansion method into the Navier–Stokes equations. The nondimensionalized governing equations were expanded in terms of the perturbation parameter, ε (channel height-to-length ratio). Experimental results obtained for the helium mass flow rate in the microchannel were shown to compare favorably with the computational results.

Gou and Wu [38] studied the gas compressibility effect on the friction factor and Nusselt number in a microtube. The study involved numerical solution of Navier–Stokes equation without any specific consideration for microchannels, other than assuming a compressible flow. It was concluded that the flow can not be considered fully developed even in long tubes, because the radial velocity profile continuously change along the tube due to compressibility effects. Therefore the product $f * \mathrm{Re}$ does not remain constant, but it is a function of Re. The Nusselt number also changes along the flow direction due to the same reason.

Compressibility and rarefaction effects were also studied by Kavehpour et al. [39]. The 2-D compressible forms of momentum and energy equations were numerically solved for flow between parallel plates with slip velocity and temperature jump at the surface for both constant wall temperature and uniform wall heat flux. The entrance (hydrodynamic and thermal) effects were also taken into account. A parametric study was performed and some important parameters such as f and Nu were calculated for a wide range of Kn, Re, and distance from the inlet for the two thermal boundary conditions. Similar calculations performed by Chen et al. [40] show that the pressure distribution along the channel is nonlinear. The nonlinearity was pronounced for higher Prandtl number. They compared their results with the experimental data obtained by Arkilic et al. [36] for nitrogen and helium. The predicted pressure distribution and mass flow rates agreed well with the experimental data.

In a theoretical work, Barron et al. [41] developed a technique for the evaluation of eigenvalues for Graetz problem extended to slip-flow in a microtube. The first four eigenvalues for Knudsen numbers in the range of 0.02 to 0.12 were found. A simplified expression for the eigenvalues as a function of Kn was presented. Using accurate values for the eigenvalues will lead to a better prediction of heat transfer in rarefied gas flows in microtubes. Yu et al. [42] calculated four additional eigenvalues and discussed the effects of these additional eigenvalues on the Nusselt number. They proposed a correlation for the Nu number in the entrance region as a function of Graetz number for a special case of $\mathrm{Kn} = 0.02$.

For the case of Knudsen number higher than 0.1 in which slip flow approximation is not valid, other methods such as direct-simulation-Monte Carlo (DSMC) can be used. Unlike the methods based on Navier–Stokes equations, DSMC approach is valid for the full range of the flow regimes (continuum through free molecular). Piekos and Breuer [43] have made use of DSMC method for simulation of channel flow. In the slip-flow regime, the results of DSMC method are in good agreement with analytical model and experimental data. Mavriplis et al. [44] and Oh et al. [45] also used DSMC method to analyze subsonic and supersonic flows in microchannels. In the subsonic flow regime, it was found that Mach number and temperature contours are in good agreement with the trends of Fanno/Rayleigh theory. One of the findings of these studies was that the temperature jump along the channel decreased, while the velocity slip remained unchanged. One of the shortcomings of DSMC method is the large amount of computing time needed for long channels.

Marongiu [46] discussed the flow compressibility issues facing the designers of microchannel heat sinks. He cautioned that choking may be a feature in compressible flow. The designer should not only check the possibility of sonic flow at the channel exit, but also the possibility of supersonic micro pockets with shock waves which must be avoided.

Finally it is useful to see the ranges of Re number encountered in the gas flow in microchannels and the possible range of transitional Reynolds numbers. Different investigators have reported different ranges of critical Reynolds number for gas flow in microchannels. Wu and Little [24] reported that the transition Reynolds number could be as low as 350–900. Most of the experiments by Pfahler et al. [26–27] were conducted at very low Reynolds number. They could not observe any transition. The experimental data reported by Choi et al. [25] covered Re up to 15000. Their results show a change in the flow behavior at Re ≈ 2500. Yu et al. [31] reported data for the values of Re in the range of 250 to 20000 (including the data for water). The correlation between the friction factor and Re changed at Re ≈ 2000, indicating a possible value for the critical Reynolds number. Harley et al. [30] reported data for the values of Re up to 1200. However, most of their data were for low Reynolds number. The experimental data reported by Shih et al. [32] are limited to Re less than 0.085. The results obtained by Arkilic et al. [36–37] are also for very low values of Re (less than 0.012).

The works reviewed in this paper are summarized in Tables 1 and 2. Table 1 corresponds to the experimental work, while Table 2 describes the theoretical work.

4
Conclusions

The results of investigations dealing with the flow and heat transfer aspects of gas flow in microchannels were reviewed. Both experimental and the theoretical works were studied. Experimental works were mainly focused on the pressure drop measurements across the flow channels of different cross sectional geometries ranging in typical dimension from 0.5 μm up. Heat transfer calculations were based on measurements of the bulk fluid inlet and outlet temperatures. The results predicted by the theory and correlations developed for conventional sized channel seem not to fit the experimental data for certain ranges of channel dimensions, Reynolds and Knudsen numbers. Theoretical works involved the slip velocity condition as well as the compressibility and rarefaction effects into the solution. These improvements helped to explain some of the differences between the theoretical and experimental data for microchannels.

Table 1. Summary of the experimental work on flow and heat transfer of gas flowing in microchannels

	Geometry	Width (μm)	Depth (μm)	Hyd. diam (μm)	Length (mm)	Flow regime	R_{crit}	Fluid	Friction factor	Heat trans. coeff.	Comments
Wu et al. [23–24]	Rectangle Trapezoid	100–200	30–65	55–83	7.5–40	Lam. Turb.	>400	N_2, He, Ar	$C^* > 1.6–5$	$H^* > 1$	1, 3
Choi et al. [25]	Tube	–	–	3–81	–	Lam. Turb.	~2300	N_2	$C^* < 1$	$H^* > 1$	2, 3
Pfahler [26–27]	Trapezoid Rectangle	75–250	0.5–20	1–35	~10	Lam.	–	N_2, He	$C^* < 1$	–	4
Pong et al. [28], Liu et al. [29]	Trapezoid Rectangle	5–40	1.2	1.2–2	3–4.5	–	–	N_2, He	$C^* < 1$	–	5
Harley et al. [30]	Trapezoid Rectangle	40	0.5–20	1–36	~10	$Re < 10^3$	–	N_2, He, Ar	$C^* < 1$	–	6
Yu et al. [31]	Tube	–	–	12–102	4.1	Re = 250–20000	~2000	N_2	$C^* < 1$	$H^* > 1$	7
Shih et al. [32]	Rectangle	40	1.2	1.2	4	–	–	N_2, He	$C^* < 1$	–	5
Bayt et al. [33]	2D Nozzle	–	19–35	–	–	–	–	–	$C^* \approx 1$	–	8

C^* is the ratio of the experimental value of the friction factor f for microchannel to that of conventional size channel. H^* is the same ratio for the heat transfer coefficients

Comments:

(1) Pressure drop much higher than that obtained from the Moody chart. Heat transfer coefficient higher than that obtained from correlation developed for conventional size channels. (2) $f * Re = 53$ for $D < 10$ μm for laminar flow. $8j_H/f$ as large as 7 was reported. (3) Nusselt is function of Re in the laminar range. Colburn analogy is not valid. (4) C^* decreases as channel depth decreases. f decreases as Re decreases for the smallest channel size. (5) Pressure distribution is not linear along the flow passage. Non-linearity is more pronounced as Knudsen number increases. Experimental results can be predicted by slip flow model. (6) Knudsen number = 0.001–0.4. (7) Higher heat transfer coefficients for turbulent flow than prediction. f varies with 1/Re. (8) Experimental results were predicted by Navier–Stoke equations

Table 2. Summary of theoretical work on the flow and heat transfer of gas flowing in microchannels

	Description of the work	Validation of results and conclusions
Beskok et al. [33–34]	Fluid flow w/o heat transfer. Complex geometries such as micro valves, micro capillaries. Slip flow. Compressibility effects. Spectral Element Technique.	Good agreement with Pfahler [26] experimental results. Further validation required for pressure drop.
Harley et al. [30]	Fluid flow w/o heat transfer. 2D channel. Knudsen number effects. Non-linear terms in Momentum eqs. neglected. 1st order correction for slip flow. locally fully developed flow assumed.	Good agreement with their own experimental results for pressure drop.
Arkilic et al. [36–37]	Fluid flow w/o heat transfer rarefied gas. 2D. NS equations with slip flow. Nonlinear terms in Momentum eqs. neglected. Perturbation method used.	Computational results compared favorably with exp. data for mass flow rate at given pressure drop.
Gou and Wu [38]	Compressibility effects on f and Nu. Non-slip condition at wall. N–S eqs solved.	Flow can not be considered fully developed because of compressibility effects. $f * \mathrm{Re}$ and Nu change along the channel.
Kavehpour [39], Chen [40]	2D compressible N–S eqs. Slip flow and temperature jump at wall. Constant wall temperature or constant heat flux. Entry length effect. Effects of Kn and Re on f and Nu.	Non-linear pressure distribution along the channel predicted. Good agreement with exp. data of Arkilic et al. [37] for pressure drop.
Baron et al. [41], Yu et al. [42]	Calculated eigenvalues for Graetz problem for tube.	Correlation for Nu in the entrance region was given.
Piekos and Breuer [43]	Direct-Simulation Monte Carlo approach was used.	Good agreement with the results of N–S Eqs. with slip flow and with exp. data was reported. Large computing time needed for long channels.
Mavriplis et al. [44], Oh et al. [45]	Direct-Simulation Monte Carlo method used for subsonioc and supersonic flows in microchannels	Velocity jump at the wall remains unchanged along the channel. Temperature jump decreases along the channel. Large computing time needed for long channels.
Marongiu [46]	Discussed flow compressibility effects facing microchannel heat sink designers.	Choking is an important feature in micro channel flow. Supersonic micro packets with shock waves must be avoided as well as the possibility of sonic flow at the exit.

Based on the results of the studies published so far on the gas flow in microchannels, several preliminary conclusions can be made.

- Although slip flow conditions implicate that the pressure drop along microchannels to be lower than the macroscale predictions, there are a number of data sets that contradict this hypothesis. This contradiction may be due to the experimental errors including the surface roughness measurement.
- Pressure distribution along the channel may be nonlinear under certain geometric and operating conditions. The real pressure distribution is determined by the viscous effects as well as by the compressibility and rarefaction effects.
- Friction factor and heat transfer coefficient in the slip flow regime can be predicted for certain range of parameters by solving Navier–Stokes equations and the conventional energy equation using velocity slip and temperature jump boundary conditions at the wall.
- The product $f * \mathrm{Re}$ is not constant as predicted by the macroscale theory for fully developed laminar flow. It is rather a function of Re number.
- No reliable range of transition Reynolds number has been reported.
- Because of the small dimensions involved, minimizing the experimental errors is a challenging task. The errors may be related to the measurement of the channel dimensions, surface roughness, unidentified blockages in the channels, unaccounted heat losses to the test structures and the surroundings and surface and fluid temperature. Another source of error is the fluctuations in the flow rate due to the flow disturbances originated from other parts of the tubing and valves.

The experimental results reported by various investigators (except in one case) so far appear to be in qualitative agreement. More experiments are needed to provide information on the effects of the following variables on the flow behavior, pressure drop and heat transfer characteristics.

The works that have been reported so far have contributed to the understanding that microchannel flow and heat transfer may not be adequately predicted by the conventional theories and correlations developed for normal sized channels. Additional work may be needed in the following areas in order to have a better understanding of the basic phenomena and to develop more reliable design correlations.

- The effects of size and geometry of channel, particularly in submicron range.
- Local pressure distribution and flow visualization on the velocity profile development.
- Non-Newtonian fluid flow in microchannels.
- Heat transfer characteristics (local and overall).
- Transitional conditions from laminar to turbulent flow.
- Effects of Knudsen number.
- Compressibility and rarefaction effects.

In theoretical front, there is an interest in having a more comprehensive understanding of the physical phenomena involved in the flow and energy transfer in microchannels, and the mathematical modeling and solution techniques.

References

1. **Fatikow S; Rembold U** (1997) Microsystem Technology and Microrobotics. Springer, pp. 1–45
2. **NEXUS** (1998) Micro System Technologies Market Study.
3. **Zengerle R; Stehr M** (1996) A New Device for Handling Fluid. mst news, NEXUS, No. 17, p 18
4. **Sen M; Wajerski D; Gad el Hak M** (1996) A novel pump for MEMS application. J Fluid Engineering 118: 624–627
5. **Bousse L; Dijkstra E; Guenat O** (1996) High density arrays of valves and interconnects for fluid switching. Proceedings Solid State Sensor and Actuator Workshop, pp. 272–275
6. **Wroblewski DE et al** (1998) MEMS Micro-valve arrays for fluidic control. In: Micro-Electro-mechanical Systems, ASME Proceedings, pp. 145–151
7. **Caruana CM** (1998) Big opening seen for microchannels. Chem Eng Prog : 13–16
8. **Veser G et al** (1998) A simple and flexible micro reactor for investigations on heterogeneously catalytic gas phase reactions. In: Micro-electro-mechanical Systems, ASME Proceedings, pp. 199–205
9. **Tonkovich AY; Zilka JL; LaMont MJ; Wang Y; Wegeng RS** (1999) Microchannel reactors for fuel processing applications, I. water gas shift reactor. Chem Eng Sci 54: 2947–2951
10. **Martin PM; Matson DW; Bennet WD** (1999) Microfabrication methods for microchannel reactors and separation systems. Chem Eng Comm 173: 245–254
11. **Tonkovich ALY; Call CJ; Jimenz DM; Wegneg RS; Drost MK** (1996) Microchannel Heat Exchangers for Chemical Reactors. AIChE Symposium Series, Heat Transfer, Houston, pp. 119–125
12. **NEXUS** (1996) Microfluidic Systems, mst news, No. 17
13. **Tuckerman DB; Pease RFW** (1981) High Performance Heat Sinking for VLSI. IEEE Electron Device Letters, EDL-2, pp. 126–129
14. **Tuckerman DB** (1984) Heat Transfer Microstructures for Integrated Circuits. PhD Thesis, Stanford University, Stanford, CA
15. **Tuckerman DB; Pease RFW** (1982) Ultra High Thermal Conductance Microstructures for Cooling Integrated Circuits. Proceedings of the 32nd Electronic Components Conference, pp. 145–149
16. **Tuckerman DB; Pease RFW** (1982) Optimized Convective Cooling Using Micromachined Structure. Electrochemical Society Extended Abstracts, Vol. 82, pp. 197–198
17. **Goodling J** (1992) Microchannel Heat Exchangers – A Review. High Heat Flux Engineering, SPIE, Vol. 1739, pp. 66–82
18. **Shaukatullah H** (1999) Bibliography of Liquid Cooled Heat Sinks for Thermal Enhancement of Electronic Packages. SEMITHERM-XV, pp. 231–245
19. **Tseng FG; Kim CJ; Ho CM** (1998) A Microinjector Free of Satellite Drops and Characterization of Ejected Droplets. MEMS, DSC, Vol. 66, pp. 89–95
20. **Selverov KP; Stone HA** (1998) Peristatically Driven Flows for Micro Mixers. MEMS, DSC, Vol. 66, pp. 85–88
21. **Byat RL; Breuer KS** (1998) Viscous Effects in Supersonic MEMS-Fabricated Micronozzles. MEMS, DSC, Vol. 66, pp. 117–123
22. **Schaff SA; Chambre PL** (1961) Flow of Rarefied Gases. Princeton University Press, Princeton, New Jersey
23. **Wu P; Little WH** (1983) Measurement of friction factor for the flow of gases in very fine channels used for micro-miniature Joule-Thompson refrigerators. Cryogenics : 272–277
24. **Wu P; Little WH** (1984) Measurement of heat transfer characteristics for gas flow in fine channel heat exchangers used for microminiature refrigerators. Cryogenics : 415–420
25. **Choi SB; Barron RF; Warrington RO** (1991) Fluid Flow and Heat Transfer in Microtubes. ASME DSC, Vol. 32, pp. 123–134
26. **Pfahler J; Harley J; Bau HH; Zemel J** (1990) Liquid and Gas Transport in Small Channels. ASME DSC, Vol. 19, pp. 149–157
27. **Pfahler J; Harley J; Bau HH; Zemel J** (1991) Gas and Liquid Flow in Small Channels. ASME DSC, Vol. 32, pp. 49–60
28. **Pong KC; Ho CM; Liu J; Tai YC** (1994) Nonlinear Pressure Distribution in Uniform Microchannel. In: Application of Microfabrication to Fluid Mechanics, ASME FED, Vol. 196, pp. 51–56
29. **Liu J; Tai Y** (1995) MEMS for pressure distribution studies of gaseous flows in microchannels. In: An Investigation of Micro Structures, Sensors, Actuators, Machines, and Systems, pp. 209–215
30. **Harley JC; Huang YH; Bau H; Zemel JN** (1995) Gas flow in microchannels. J Fluid Mech 284: 257–274
31. **Yu D; Warrington R; Barron R; Ameel T** (1995) An Experimental and Theoretical Investigation of Fluid Flow and Heat Transfer in Microtubes. ASME/JSME Thermal Engineering Conference, Vol. 1, pp. 523–530
32. **Shih JC; Ho C; Liu J; Tai Y** (1996) Monatomic and Polyatomic Gas Flow Through Uniform Microchannels. National Heat Transfer Conference, DSC, Vol. 59, pp. 197–203
33. **Bayt RL; Breuer KS** (1998) Viscous Effects in Supersonic MEMS-fabricated Micronozzles. ASME DSC, Vol. 66, MEMS, pp. 117–123
34. **Beskok A; Karniadakis GE** (1994) Simulation of heat and momentum transfer in complex micro geometries. AAA J Thermal Heat Transfer 8(4): 647–655
35. **Beskok A; Karniadakis GE; Timmer W** (1996) Rarefaction and compressibility effects in gas micro flow. J Fluid Eng 118: 448–456
36. **Arkilic E; Schmidt M; Breuer K** (1994) Gaseous Flow in Microchannels. ASME Winter Annual Meetings in Chicago, IL, November 1994, pp. 57–65
37. **Arkilic EB; Schmidt MA; Breuer KS** (1997) Gaseous flow in long microchannels. J Microelectromechanical Syetems 6(2): 167–178
38. **Guo ZY; Wu XB** (1997) Compressibility effect on the gas flow and heat transfer in a microtube. Int J Heat Mass Transfer 40(13): 3251–3254
39. **Kavehpour HP; Faghri M; Asako Y** (1997) Effects of compressibility and rarefaction on gaseous flows an microchannels. Numerical Heat Transfer, Part A 32: 677–696
40. **Chen CS; Lee SM; Sheu JD** (1998) Numerical analysis of gas flow in microchannels. Numerical Heat Transfer, Part A 33: 749–762
41. **Barron RF; Wang X; Warrington RO; Ameel T** (1996) Evaluation of eigenvalues for Graetz problem in slip-flow. Int Comn Heat Mass Transfer 23: 563–574

42. **Yu D; Warrington RO; Ameel TA; Barron RF; Wang X** An Improved Solution to the Graetz Problem with Slip-flow. 4th International Symposium on Heat Transfer, Bejing
43. **Piekos ES; Breuer KS** (1995) DSMC Modeling of Micromechanical Devices. AIAA paper 92-2085
44. **Mavriplis JC; Goulard R** (1997) Heat transfer and flow fields in short microchannels using direct simulation Monte Carlo. J Thermophysics Heat Transfer 11(4): 489–496
45. **Oh CK; Oran ES; Sinkovits RS** (1997) Computation of high-speed, high Knudsen number microchannel flows. J Thermophysics Heat Transfer 11(4): 497–505
46. **Marongiu MJ** (1996) Compressibility Effects in Design of Gas-cooled Microchannel Heat Sinks. Intersociety Conference on Thermal Phenomena, pp. 124–129