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 cannot be accurately 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
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, microdosing 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.