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On Micro-Channel Flow and Mixing: A Review

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Abstract

This paper presents a review of the important recent literature available in the area of micro-channel flow analysis and mixing. The topics covered include the physics of flows in micro-channels and integrated simulation of micro-channel flows. Also the flow control models and electro-kinetically driven micro-channel flows are explained. A comparison of various mixing principles in micro-channels are provided in sufficient detail.

1. INTRODUCTION

Micro-channels are flow domains, having their internal dimensions within the range of 1mm and 1μm. The most salient macroscopic flow behavior, in general, extends at most up to 1mm only. Due to various advantages that micro-channels offer, their applications range from compact heat exchangers to MEMS devices that are used for biological and chemical analysis. At present, micro-channels are used to transport and mixing biological materials such as proteins, DNA, cells, etc. or to send chemical samples from one place to the other. A comprehensive coverage about micro-channel applications and the important aspects of the micro-channel flow are provided by Gad-el-Hak [1].

The physics of flow and heat transfer in micro-channel devices is found to be quite different from that of macro-scale devices. A well known example for this is the failure of Fourier law to predict the thermal conductivity of micro-structures [2]. Luckily, the potential interaction distance is very small in typical liquid systems and the continuum description is valid for most micro systems, as well. Fluid flow in micro-channels typically requires higher pressure differences and the flow rates are very small. The micro-channel flow phenomena often demand a different way of analysis and special numerical tools.

The understanding of the unconventional physics involved in the manufacture and operation of small devices is crucial for designing, optimizing, fabricating and utilizing the improved MEMS. In dealing with the flow through micro-devices, the selection of physical and mathematical models, boundary conditions and solution procedure are quite critical. It is well known that the surface effects are going to dominate in micro-devices [3]. The million-fold increase of surface area relative to the mass of the minute devices (per unit volume), substantially affects the transport of mass, momentum and energy through the surface.

The importance of mixing in micro-channels can never be under-estimated. Efficient micro-mixers are vital for the successful operation of bio-fluid systems. The performance of these devices depends largely on the rapid and efficient mixing of different fluids. This has to be achieved, in spite of the difficulties put forth by the fundamental physics of flow in narrow channels, with high viscosity and low Reynolds number values. Various alternatives are being tried with the aim of reaching the final goal, which is instantaneous mixing [4]. Also, the effect of fluid mixing needs to be considered in many other micro-systems, like fluid control and pumping systems, where the major aim may be reducing the pressure drop [5].

A major difficulty in connection with the micro-channel analysis is the geometrical complexity of the flow domain. Numerous designs of micro-channels have been proposed, including T and H shaped channels, zigzag shaped channels, 2D and 3D serpentine channels and multi-laminators. The T-sensor designed by Weigle and Yager [6] for implementation of assays in micro-channels is quite popular. In this design a reference stream, a detection stream and a sample stream are introduced through multiple T junctions into a common channel. Differential diffusion rates are also fundamental to the design of H-filter, used to separate components [7]. Splitting the streams and re-layering increases the interfacial area which promotes mixing. This layering approach was implemented by Branebjerg et al. [8]. By adding complexity to the flow field, this has good potential to increase the amount of mixing between

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the streams. The three dimensional serpentine channel proposed by Lie et al. [4] was designed to introduce chaotic advection into the system and further enhance mixing.

Another aspect which has to be taken care of, in the case of micro-channel flow and mixing, is the electro-kinetic effect. Electro-kinetics is the general term describing phenomena that involve the interaction between solid surfaces, ionic solutions and macroscopic electric fields. Both electrophoresis and electro-osmosis phenomena need to be considered in micro-channel flow analysis. The fluid pumping that occurs in a micro-capillary when an electric field is applied along the axis of the capillary [9] is a typical example of the latter. These interactions between charged particles and electric fields often involve electric double layers formed at liquid/solid interfaces.

For a larger class of flows, Navier-Stokes equations based on the continuum assumption are adequate to model the fluid behavior. Continuum approximation implies that the mean free path of the molecules, λ in a gas is much smaller than the characteristic length, L. That is, the Knudsen number, Kn $(=\lambda/L)$ has to be very small ($<<1$). However, there are special cases in micro-channel flow, that does not satisfy this condition. The various flow regimes and suitable fluid models are shown in Table 1 [10].

TABLE 1 Flow regimes & fluid models for micro-channels

Knudsen Number	**Fluid Model**
$Kn \to 0$ (continuum, no molecular diffusion)	Euler equations with slip-boundary conditions
$Kn \le 10^{-3}$ (continuum, with molecular diffusion)	Navier-stokes equations with no-slip-boundary conditions
$10^{-3} \le Kn \le 10^{-1}$ (continuum-transition)	Navier-stokes equations with slip-boundary conditions
$10^{-1} \le Kn \le 10$ (transition)	Burnett equations with slip-boundary conditions Moment equations DSMC
$Kn > 10$ (free molecular flow)	Lattice Boltzmann Collisionless Bltzmann DSMC Lattice Boltzmann

As shown in this table, Navier-Stokes equation together with Boltzmann equation describes the flow in all regimes. For the accurate prediction of the flow parameters in micro-channels, it is very important that a suitable numerical tool is used for the analysis. Often in the literature it is found that the standard Navier-Stokes solvers are extended to yield solution for micro-channel flow parameters. While doing so, one should be very careful to incorporate the additional considerations with respect to the micro-channels. Along with the Navier-Stokes solvers, molecular based numerical simulation methods (for example, the lattice Boltzmann method) for liquid and gas micro-flows are also being tried.

In the micro-scales, fluid stirring becomes one of the most crucial factors in design and operation of micro-devices. A discussion on the passive and active micro-mixers is presented in Sec. 2. A brief note about the electro-kinetic transport and determination of mixing efficiency is given in Sec. 3 and Sec. 4, respectively.

2. PASSIVE AND ACTIVE MICROMIXERS

The application of micro-mixers range from the modern sample preparation for the lab-on-chip devices to traditional mixing tanks for purposes such as, blending, reaction, gas absorption, foaming and emulsification [11-13]. The flow rates in micro-mixers range from as low as less than 1 ml/h to more than 1,000 l/h; covering the whole flow range up to the conventional static mixers. By-and-large, the micro-flow and mixing is typically done in the laminar regime at very low Reynolds number values [14].

In micro-fluidic devices, the mixing relies solely on molecular inter-diffusion [15], due to the absence of turbulence. Diffusive mixing can be optimized by maximization of the constitutive factors like the diffusion coefficient, interfacial surface area and the gradient of species concentration. Basically, ‘the art of micro-mixing’ translates to an efficient maximization of the interfacial surface area and concentration gradient. Also, convective diffusion is commonly employed in the mixing devices.

Mixing in micro-scale is performed either by energy input from the exterior (active mixing) or by the flow energy due to pumping action/hydrostatic potential (passive mixing). Tables 2 and 3 gives the various options available in these categories (respectively), and the corresponding literature references. Some typical generic micro-structure designs employed for passive mixing includes the following [31].

(i) T and Y flow configurations
(ii) Inter-digital and bifurcation flow distribution
(iii) Focusing structures for flow compression
(iv) Repeated flow division and recombination
(v) Flow obstacles within micro-channels
(vi) Meander-like or zig-zag channels
(vii)Multi-hole plates
(viii)Tiny nozzles
(ix) Specialty flow arrangements

3. ELECTROKINETIC TRANSPORT

This refers to the combination of electro-osmotic and electro-phoretic transport. A detailed review of electro-kinetics in micro-fluidics is available in a recent publication by Li [32]. Electro-osmosis is the bulk movement of aqueous solution past a stationary solid surface, due to an externally applied electric field. Electro-osmosis requires the existence of a charged double layer at the solid-liquid interface. This charged double layer is usually very thin and results from the attraction between bound surface charges and ions in the passing fluid. Electro-phoresis describes the motion of a charged surface submerged in a fluid under the action of an applied electric field. Considering the case of a charged dye molecule, the electro-phoretic velocity of the dye is described by the Helmholtz-Smoluchowski equation. The electro-osmotic zeta potential is a property of the capillary surface while the electro-phoretic zeta potential is a property of the charged dye and in general, these two zeta potentials will not be equal.

TABLE 2 Active mixing by external energy input

External energy source	Reference
Ultrasound	Yang et al. [16]
Acoustically induced vibrations	Liu et al. [17]
Electro-kinetic instabilities	Oddy et al. [18]
Variation of pumping capacity	Glasgow & Aubry [19]
Electro-wetting induced droplets	Palk et al. [20]
Piezo-electric vibrating membranes	Woias et al [21]
Magneto-hydrodynamic action	West et al. [22]
Small impellers	Lu et al. [23]
Integrated micro-valves/pumps	Voldman et al. [24]

TABLE 3 Passive mixing by pumping power

Principle	Reference
Inter-digital multi-lamellae arrangement	Lob et al [25]
Split-and-recombine concepts	Schonfeld et al. [26]
Chaotic mixing by eddy formation And folding	Jiang et al. [27]
Nozzle injection in flow	Miyake et al. [28]
Collision of jets	Werner et al. [29]
Specialties like the Coanda-effect	Hong et al. [30]

4. MIXING EFFICIENCY

The easiest method for judging the mixing efficiency in micro-mixer structures is by flow visualization, which is done using dilution-type experiments [33]. Reaction-type experiments underlay the mixing with very fast reaction so that mixed region spontaneously indicate the result of the reaction. Roessler and Rys [34] introduced two parallel reactions (competitive reactions) which develop differently under varying pH, solvent, etc. This in turn, can be used as a measure of the mixing efficiency. By properly designing the micro-channel manifold, one can accomplish parallel and serial electro-kinetic mixing using a simple voltage-control circuit [35]. Mixing on micro-fluidic devices typically occurs by the interplay of molecular diffusion and pressure-driven convection (dispersion) in the laminar regime. Mixing rates can be enhanced by using the principle of flow lamination [36], whereby the streams are divided into n laminae with widths $1/n$ of the original channel. This can result in faster mixing by a factor of n^2.

5. CONCLUSIONS

The micro-channel flow analysis is receiving wide attention presently, owing to its high utility potential in many multi-disciplinary applications. Often it is required to use special numerical techniques for the analysis of flow phenomena in micro-devices. Some of the CFD tools being tried in the recent past, by researchers for the analysis of micro-channel flows include the Lattice Boltzmann Method (LBM) and the Immersed Boundary Method (IBM).

The choice of micro-structured mixers is sufficiently broad. However, there are many unresolved issues with respect to micro-mixers which need to be addressed, presently. There is still room for new designs and principles in this field. More robust and professional designs are needed and field trials have to be conducted to evaluate the potential in an industrial environment. Also benchmarking has to be done and the existing micro-mixers are to be categorized more scientifically.

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