Microfluid Nanofluid
DOI 10.1007/s10404-013-1254-1

RESEARCH PAPER

# Numerical predictions of backward-facing step flows in microchannels using extended Navier–Stokes equations

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Received: 29 January 2013 / Accepted: 13 August 2013


**Abstract** Flows in microchannels were successfully predicted, in the past, both analytically and numerically, employing the extended Navier–Stokes equations (ENSE). In ENSE, the self-diffusion transport of mass, together with the resulting momentum and heat transport, is taken into account properly and the same is omitted in the classical Navier–Stokes equations. The ENSE have been employed here to numerically predict backward-facing step flows in microchannels, and the predictions are summarized in this paper. The results obtained by employing ENSE are compared with the available literature data computed by both direct simulation Monte Carlo and slip-velocity-based simulations. The good agreement of the present results with those given in the literature evidently points out that the ENSE can be applied to gas flows through complex microchannel geometries.

## 1 Introduction

The flow conduits in Micro-Electro-Mechanical-Systems (MEMS) may not be simple straight channels and capillaries. They often involve complex geometries including steps and abrupt turns and bends. Therefore, analyzing gas flows through complex microgeometries is of immense importance, and for this reason, this particular topic has continued to attract the interest of researchers over the years. Agrawal et al. (2009) simulated gas flows through 90$^{o}$ bends employing the slip flow theory and the lattice Boltzmann method (LBM). Simulation of gas flows over backward-facing steps in microchannels is considered to be one of the benchmark problems to demonstrate the effectiveness of theoretical models and computational techniques in microscale flows. A number of studies have applied the LBM or the direct simulation Monte Carlo (DSMC) method along with the 'slip flow' theory employed in microchannels. Agrawal et al. (2005) simulated gas flows in microchannels with a sudden expansion or contraction in order to obtain insight into flows in complicated microdevices. They employed the LBM, and the computations were performed for several area and pressure ratios over a range of Knudsen numbers in order to assess the effects of compressibility and rarefaction.

Wu and Lee (2001) demonstrated the usefulness of the DSMC method in simulating gas flows through backward-facing microstep geometries. Kursun and Kapat (2007) also employed the DSMC method to simulate flows through microchannels with a backward-facing step. The simulations in this case were conducted with Reynolds numbers of 0.03–0.64, Mach numbers of 0.013–0.083, and Knudsen numbers of 0.24–4.81. In these parameter ranges, they did not observe any separation region in the flow geometry. They employed an information preservation (IP) method to separate the macroscopic velocity from the molecular velocity, and hence, the typical statistical noise generated in DSMC simulations was minimized in this way.

Beskok (2001) also employed the DSMC method to simulate high-velocity gas flows through microchannels with a backward-facing step. Celik and Edis (2007) also

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Published online: 05 September 2013