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**Keywords:** Rarefied flow; porous media; transition regime; Direct Simulation Monte Carlo; Lattice-Boltzmann; mesoscopic methods.

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**Graphical abstract**

INTRODUCTION

Recent advances in microtechnology and, in particular, in microelectromechanical systems (MEMS) and nano porous media have necessitated the elucidation of flow and transport processes in small dimensions. This is also the case with several other industrial applications, which rely on low-pressure conditions, or

the molecular time and length scales are not sufficiently small compared to the characteristic macroscopic flow scales.

The various flow regimes and the corresponding governing equations are summarized in Fig. 1 (see also [1]).

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**Figure 1:** Flow regimes and governing equations.

In the context of this work a description of recent advances in simulation techniques, namely, the “continuum” slip approaches [1, 9], and direct mesoscopic techniques, such as the Direct Simulation Monte Carlo (DSMC) method [8, 10-12], the Information Preservation (IP) method [13-16], and the Lattice Bolzmann (LB) method [17-18], are presented. Illustrative simulation results of permeability and viscosity coefficients in mesoporous media using the

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Following eq. (1.), the Knudsen number can be expressed as

 ()

where  is a characteristic macroscopic flow dimension.

Several methods to simulate rarefied flows have been proposed, which fall into two main categories, namely macroscopic and microscopic approaches. The former consist of the direct solution of the Navier-Stokes equation or semi-empirical equations with appropriate boundary condition to induce the slip effect, whereas the latter consist of either direct or stochastic particle monitoring methods using kinetic theory descriptions, such as Molecular Dynamics (MD) and Monte Carlo (MC) methods. Even though the microscopic approaches are more accurate inherently, most processes involving porous media and micro-sized devices (*i.e.* MEMS) would require enormous CPU resources to be simulated effectively.

Strictly, the continuum condition (Fig. **1**) prohibits the use of the Navier-Stokes equation for non-zero Knudsen numbers. Nevertheless, by introducing slip boundary conditions, Arkilic and coworkers [9] proposed a two-dimensional scheme for rarefied flows involving the Navier-Stokes equation and a first order boundary condition, proposed by Maxwell [2] (Fig. **2**), which reads

 ()



**Figure 2:** Slip velocity at the wall.

**Table 1:** Thermo physical properties.

|  |  |  |
| --- | --- | --- |
|  | T (°C) | Cp (kJ.kg-1.K-1) |
| Water | 25 | 4.18 103 |
| Air | 25 | 1.01 103 |

. ()

The authors [12] further simplified the boundary condition in order to avoid the calculation of the 2nd order velocity derivatives that may introduce computational difficulties, to the following slip boundary condition

, ()

where *b* is a parameter that “incorporates” the 2nd order derivative term and takes the value *b* =-1 for fully developed flow in a channel.

CONCLUsions

The need to describe rarefied flows in a variety of applications that involve micro, and nanoscale pores or channels has stimulated the development of a multitude of theoretical and numerical methodologies. A comparison of the predictions of the mesoscopic approaches with those of the Navier-Stokes formulation complemented by a non-slip flow condition revealed that the latter can be safely employed for very small Knudsen number values only. The DSMC method was used to determine the flow field in different types of porous media and processes.

Conflict of Interest

To be declare if it is required

Acknowledgement

To be declare if it is required

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