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AN INSIGHT VIEW OF PRESSURE, TEMPERATURE AND BOUNDARY DRIVEN FLOWS BASED ON DSMC DECOMPOSITION

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ABSTRACT

In gas flows under highly rarefied conditions, where the mean free path is comparable to the characteristic length scale of the flow, interesting non-equilibrium phenomena appear. Such flows are characterized by high values of the Knudsen number and are typically encountered in vacuum applications or micro-electromechanical systems. Due to the long mean free paths, at each point of the flow domain, even far from the vicinity of the walls, the particle distribution is composed of particles arriving directly from the boundaries without interacting with other particles and particles arriving after an arbitrary number of collisions. The former group of particles is called ballistic part and the latter one - collision part of the distribution function. The particles that belong to the ballistic part are emitted from the boundaries and travel well into the bulk of the flow, according to the boundary distribution which, in general, differs significantly from the relaxing distribution (following a collision) encountered in their path. In order to quantitatively study the non-equilibrium phenomena that result from this, the distribution function is decomposed into the ballistic and collision parts, using the Direct Simulation Monte Carlo (DSMC) method, introducing a tag on each particle that indicates whether it belongs to the ballistic or collision part and adjusting accordingly the sampling procedure.

This DSMC decomposition procedure has been recently used in order to investigate two thermally driven flows in rectangular cavities. In the first case, the bottom and top walls were kept at constant and different temperatures, while a linear temperature distribution between those temperatures is applied to the lateral walls [1]. It has been observed that a flow near the lateral boundaries was formed, having a velocity from hot-to-cold regions, contrary to the thermal creep flow. In the second case, three walls of the cavity were kept at a constant low temperature and the fourth one at a higher temperature [2]. It has been found that the heat flux departing from the hot wall, for some given Knudsen number, has a non-monotonic behavior with respect to the temperature ratio with a maximum heat flux appeared at some intermediate ratio (Fig. 1a). In both configurations the decomposition technique provided solid physical explanation of the observed unexpected non-equilibrium phenomena. Furthermore, the same DSMC decomposition has been applied to provide a quantitative explanation to the classical Knudsen minimum, observed in fully developed flows though long, straight capillaries of various cross sections [3] (Fig. 1b).

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In the present work the DSMC decomposition methodology is briefly described and its implementation to the above flow setups is reviewed. In addition, this methodology is also applied to two other configurations. The first one is the classical rarefied gas flow between two concentric cylinders, with the inner one rotating at a constant speed and the outer one being stationary. As it is well-known at some small values of the tangential momentum accommodation coefficient of the outer cylinder α, and of the gas rarefaction δ, an inversed velocity profile is observed and the maximum gas velocity is not at the rotating cylinder. This non-equilibrium phenomenon is also investigated using the decomposition technique and some useful insight in addition to the available prediction is provided. The second configuration is the fully developed flow through long curved channels. In contrast to the straight capillary case, if the curvature of the channel is adequately large the Knudsen minimum may not exist and a monotonous behavior of the flow rate is observed.

Indicative results for the those configurations are presented. Fig. 1a shows the heat flux departing from the heated wall of a square cavity, along with its ballistic and collision parts, for various values of the temperature ratio. The maximum value of the heat flux is observed for a temperature ratio around 0.3 and can be explained by the different slopes of the two parts. In Fig. 1b, the reduced flow rate and its ballistic and collision parts are presented in terms of the rarefaction parameter, for pressure driven flow between parallel plates. In this case, as the rarefaction parameter increases, the collision (or drift) part of the flow rate increases, while the ballistic part decreases with a higher rate. This difference in the rate of change of those two parts, creates a minimum flow rate, known as the Knudsen minimum. In Fig. 1c, the inverted velocity profile, along with the ballistic and collision parts of the velocity in the cylindrical Couette flow are provided. The increase and decrease rates of the collision and ballistic velocities respectively justify the observed inverted velocity distribution between the cylinders.

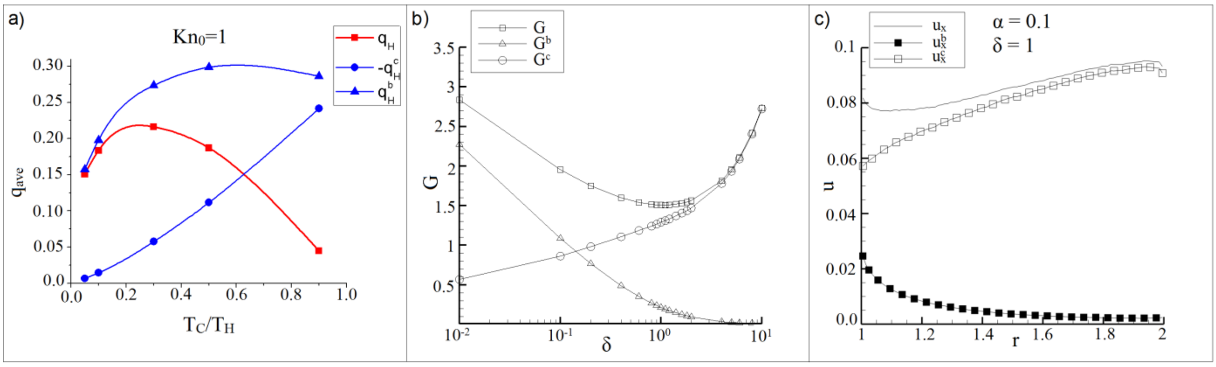

Figure 1: Indicative results for a) the heat flux departing from the heated wall of a cavity, b) the fully developed flow between parallel plates and c) the inverse velocity profile in the cylindrical Couette flow.

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