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LARGE KNUSDEN THERMALLY-DRIVEN GAS FLOWS OVER BACKWARD FACING STEPS

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KEY WORDS

Microchannel step flow, free-molecular flow, flow detachment, thermally-driven flows, gas-surface interactions.

ABSTRACT

The flow over a backward step is a canonical problem in fluid mechanics, which has been studied extensively over the years as a model problem for illustrating fluid flow over a sharp discontinuity, and describing flow separation and reattachment phenomena. Recent developments in the field of micro-electro-mechanical systems (MEMS) have led to an increasing number of investigations of the step problem at small-scale devices containing micro-channel geometries, as reviewed in Ref. [1]. Within the context of rarefied gas flows, several works have applied the direct simulation Monte Carlo (DSMC) method to analyze the problem at arbitrary Knudsen (*Kn*) numbers, and investigate the impact of gas heat transfer on the flow field (e.g., [2,3]). As these works are based on DSMC computations, their scope is inevitably limited by the drawbacks of the numerical method, and may benefit from exact analysis of the kinetic equations. Focusing on the limit of large gas rarefaction, the primary objective of the present contribution is to provide such an insight through rigorous investigation of the free-molecular flow problem.

Towards this end, we consider the two-dimensional steady channel flow of a rarefied gas over a backward facing step in the limit of large Knudsen numbers. The ballistic problem is solved analytically for both diffuse and specular reflecting channels, and the solutions are validated through comparison with DSMC calculations. Prescribing the density and temperature differences between the inlet and outlet external states (modeled as equilibrium Maxwellians with zero bulk velocity), as well as the channel walls temperatures in the diffuse-reflecting setup, the results for the inlet-to-outlet density- and temperature-drop-driven flows are analyzed and contrasted, revealing higher flow velocities and mass flow rates in the former. While the flow rate is unaffected by the step geometry in the specular case, it increases with the step size in the diffuse reflecting setup. At conditions where small flow velocities occur, flow detachment is observed in the form of streamlines connecting the step edges stagnation points. Considering the problem at finite Knudsen numbers, the ballistic flow regime breaks down at higher Knudsen numbers for lower gas speed flows, followed by the occurrence of step flow separation and recirculation.

Some of our findings are illustrated in the attached three figures. Focusing on a temperature-driven flow setup in a diffuse reflecting channel, all figures pertain to configurations where the ratio *R* between the outlet and inlet reservoir gas temperatures is smaller than unity, and the gas densities are equal. The channel walls temperatures are chosen equal to the inlet reservoir temperature. Considering a large (R=0.1) temperature drop setup, Figure 1 shows the flow streamlines and gas speed map in the free-molecular regime for a channel with unity step height s=1 (in inlet size units). As expected from previous studies, the flow field appears fully attached at the step, and no separation occurs in the ballistic case. Yet, qualitatively different results are obtained when lower-speed setups, driven by higher (closer to unity) R values are taken. This is demonstrated in Figure 2, showing, for R=0.8 and a larger step size (s=3), a zone in the vicinity of the step surface where the flow streamlines originate and end at the step upper and lower edge points, respectively. Marking these streamlines by dashed curves, the extent of this zone increases with increasing R and s, occupying nearly half of the downstream wall for the setup shown in Fig. 2. This is accompanied by an overall decrease in the flow velocity amplitude, as depicted by the speed colormap. Notably, the detached zone is quantitatively different from the recirculation-flow pattern common at lower Knudsen numbers, where closed contour streamlines are formed (see Fig. 3). The present type of flow detachment may nevertheless be of fundamental and practical significance, as the gas located in the dashed streamlines zone is separated from the bulk fluid and does not transport to the channel outlet. Finally, Figure 3 shows DSMC-calculated results for the effect of the Knudsen number on the flow field. Considering the same large-temperature-drop conditions as in Fig. 1, the figure shows that "conventional" flow separation occurs already at the relatively large Kn=5 case presented, combined with flow velocities higher than in the collisionless case. These and additional results will be discussed and rationalized in the full paper version of the work.

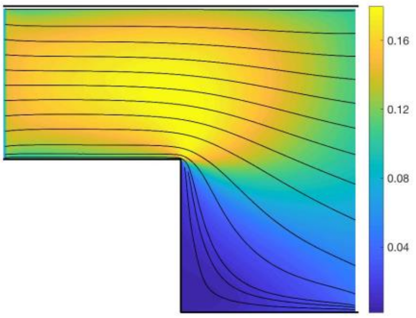

Figure 1: Flow streamlines (curves) and gas speed (colormap) in the free-molecular regime for a diffuse reflecting channel with unity step size (in inlet size units) and outlet to inlet reservoir temperature ratio R=0.1.

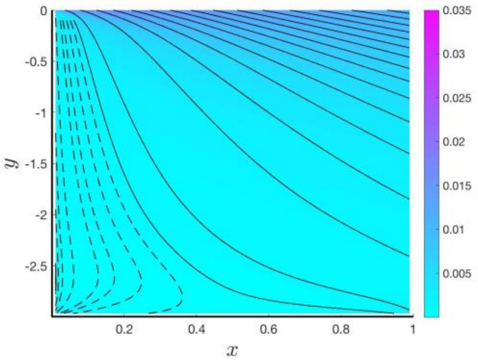

Figure 2: Flow streamlines (curves) and gas speed (colormaps) downstream of the step wall (the y-axis) at free-molecular conditions, for a diffuse reflecting channel with step size s=3 (in inlet size units) and outlet to inlet reservoir temperature ratio R=0.8.

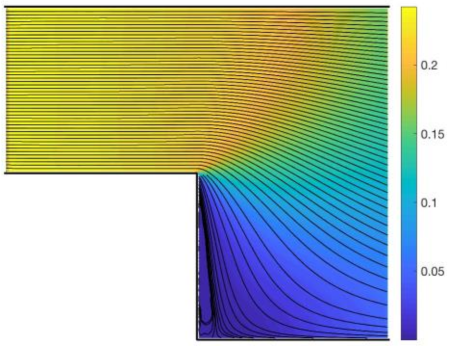

Figure 3: Effect of the inlet-based Knudsen number (*Kn*=5) on the flow streamlines (curves) and gas speed (colormap) for a diffuse reflecting channel with unity step size (in inlet size units) and outlet to inlet reservoir temperature ratio *R*=0.1.

References

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