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A SIMPLE METHOD FOR CAPTURING SOME COMPLEX PHYSICS OF GAS FLOWS IN MEMS

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ABSTRACT

One difficulty in accurately modelling micro-scale gas flows is that the flow behaviour is generally dominated by the influence of any solid bounding surfaces. The non-equilibrium phenomena introduced by a solid surface are qualitatively different to that generated by the variation of hydrodynamic variables alone; if the wall is assumed to behave like a Maxwellian emitter, a discontinuity is introduced in the distribution function.

Continuum-based methods (such as those, including the conventional Navier-Stokes equations, which can be derived from perturbation series solutions of the Boltzmann equation) are unable to resolve properly the region of local non-equilibrium that exists one or two molecular mean free paths from the wall in any gas flow near a surface. This region is called the “Knudsen layer” or “kinetic boundary layer” and recent comparisons of Knudsen layer predictions from a number of current high-order equation sets and concluded that none could be considered both reliable and accurate [1]. This is problematic for the future design and application of micro and nano flow devices because the momentum and energy fluxes from the region of the Knudsen layer to the boundaries has a critical influence on the overall flow behaviour.

Although not definitively proving that continuum equation sets are incapable of accurately modelling near-wall behaviour, there is therefore strong evidence to suggest that — if continuum equations are to be used at all — alternative phenomenological approaches may be just as useful in these non-equilibrium regions.

In this paper we demonstrate a simple phenomenological technique for introducing non-equilibrium effects caused by the presence of solid surfaces into the current fluid dynamics framework. By combining a new model for slip boundary conditions with a near-wall scaling of the Navier-Stokes constitutive relations, we obtain a model that is much more accurate at higher Knudsen numbers than the conventional second-order slip model. We show that it provides good results for Poiseuille (see figure 1) and combined Couette/Poiseuille flow, and that it can predict the stress-strain-rate inversion that molecular simulations show is evident in the latter. The model’s generality to non-planar geometries is demonstrated by examining low-speed flow around a micro-sphere.

It shows a marked improvement over conventional predictions of the drag on the sphere, although there are some questions regarding its stability at the highest Knudsen numbers.

REFERENCES

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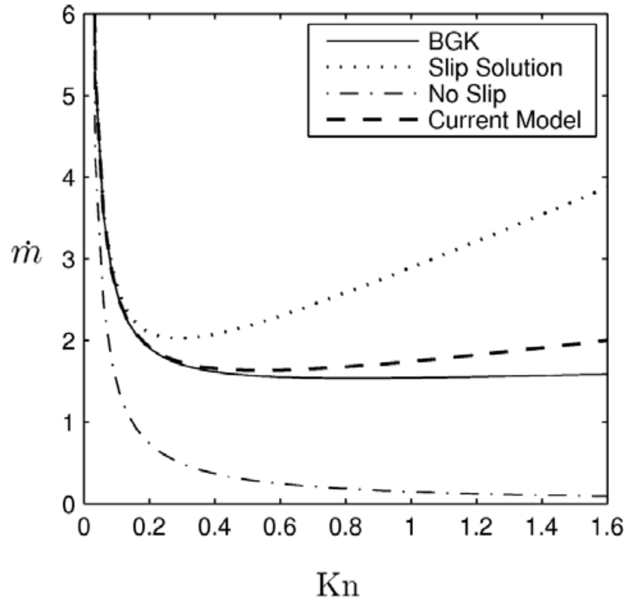

Figure 1. Normalized mass flowrate predictions for gas micro Poiseuille flow up to Kn=1.6. Comparison of no-slip solution (– ·), slip solution (···), BGK kinetic theory (–), and our model (– –).