Velocity inversion in cylindrical Couette gas flows

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Abstract

We investigate a power-law probability distribution function to describe the mean free path of rarefied gas molecules in non-planar geometries. A new curvature-dependent model is derived by taking into account the boundary-limiting effects on the molecular mean free path for surfaces with both convex and concave curvatures. In comparison to a planar wall, we find that the mean free path for a convex surface is higher at the wall and exhibits a sharper gradient within the Knudsen layer. In contrast, a concave wall exhibits a lower mean free path near the surface and the gradients in the Knudsen layer are shallower. The Navier-Stokes constitutive relations and velocity-slip boundary conditions are modified based on a power-law scaling to describe the mean free path, in accordance with the kinetic theory of gases, i.e. transport properties can be described in terms of the mean free path.

Velocity profiles for isothermal cylindrical Couette flow are obtained using the power-law model. We demonstrate that our model is more accurate than the classical slip solution, especially in the transition regime, and we are able to capture important non-linear trends associated with the non-equilibrium physics of the Knudsen layer. In addition, we establish a new criterion for the critical accommodation coefficient that leads to the non-intuitive phenomena of velocity-inversion. Our results are compared with conventional hydrodynamic models and direct simulation Monte Carlo data. The power-law model predicts that the critical accommodation coefficient is significantly lower than that calculated using the classical slip solution and is in good agreement with available DSMC data. Our proposed constitutive scaling for non-planar surfaces is based on simple physical arguments and can be readily implemented in conventional fluid dynamics codes for arbitrary geometric configurations.