Oscillatory Couette Flows: Bounded Stokes and Rarefaction Layers

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A complete mathematical description of oscillatory Couette flows within the framework of kinetic theory is not available in the literature. Motivated by this and their vast engineering applications, we present a parametric study of time-periodic oscillatory Couette flows using the unsteady direct simulation Monte Carlo DSMC method. Computations are performed as a function of the Knudsen Kn and Stokes β numbers, in the entire Knudsen regime ($Kn \leq 100$) and a wide range of Stokes numbers ($\beta \leq 7.5$). The DSMC results are validated using a recently developed semi-analytical/empirical model that is applicable for quasisteady flows ($\beta \leq 0.25$) in the entire Knudsen regime, and for any Stokes number flow in the slip flow regime ($Kn < 0.1$). In addition, we derived an analytical solution of the linearized collisionless Boltzmann equation for oscillatory Couette flows, and utilized this to validate the DSMC results in the free-molecular flow regime. Dynamic response of the flow, including the velocity profiles, phase angle, wave speed, shear stress, and the penetration depth for high Stokes number flows are presented. Increasing the Stokes number at fixed Kn, we observed formation of ‘‘bounded Stokes layers,’’ as expected. However, increasing the Knudsen number at fixed β results in ‘‘bounded rarefaction layers,’’ where the penetration depth continuously decreases with increasing the Kn. Interplay between the rarefaction and unsteadiness contributes to this interesting flow physics, and also introduces a new characteristic length scale to the problem.