

Numerical Simulation for Micro Gas Flows Using Boltzmann Equations

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This paper describes a numerical method using the model equations of the Boltzmann equations for simulating gas flows in micro scales, where the Knudsen number is moderately large and the continuum assumption may no be valid. The direct simulation Monte Carlo (DSMC) method [1], which is the powerful simulation tool for hypersonic rarefied gas flows, is unsuitable for the low Mach number gas flows in micro scales, because tremendous sample size is required to distinguish the small variation of pressure and density distributions from its inherent large statistical scatter [2]. The appearance of an alternative method is highly desired.

The CFD method based on the model equations of the Boltzmann equation [3, 4], which is rather expensive for hypersonic flow simulation [5], competes with the DSMC method for supersonic flow simulation and is definitely superior to it for subsonic flow simulation. For example, Fig. 1 shows the comparison of the density contours obtained with the CFD method using the higher order model Boltzmann equation [3] and with the DSMC method for the supersonic flow around a circular cylinder at the free stream Mach number of 2.0 and Knudsen number of 0.1. The results obtained with the both methods for the full flow field around the circular cylinder, while the result of the present method is plotted for the upper half flow field and the DSMC for the lower half flow field. The pressure distributions obtained along the front stagnation line are compared in Fig. 2. The results obtained with the Navier-Stokes equations using the velocity slip and temperature jump boundary conditions are also plotted in the figure. The CFD method using the model Boltzmann equation competes with the DSMC method in reliability as well as efficiency

For the subsonic flow, the DSMC method is no match for the present method. Figure 3 shows the comparison of the pressure contours obtained at the free stream Mach number of 0.1 and Knudsen number of 0.1. No meaningful result is obtained with DSMC method even for using more than ten times as long as the CPU time of the present method. The comparison with the results using the Navier-Stokes equations with the velocity slip and temperature jump boundary conditions are made in Fig. 4. The good comparison is obtained except for the wake region where the rarefaction effect further increases.

Figure 5 shows the density contours on a sphere surface at a free stream Mach number of 0.01 and Knudsen number of 0.1. The flow simulation is carried out for the full three dimensional flow field around the sphere using an unstructured grid. Figure 6 shows the comparison of the drag coefficients. The good comparison is obtained between the present results and the analytic results of Barber and Emerson [6].

A full description of the numerical method based on the Boltzmann equation and further numerical results including the hybrid method using the Boltzmann and the Navier-Stokes equations will be presented in the final paper.

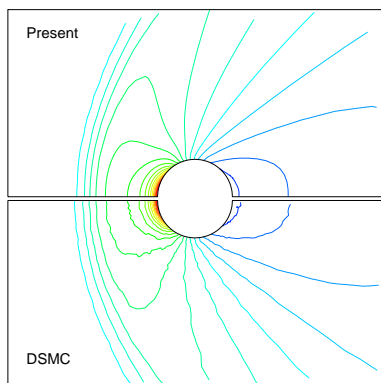


Figure 1: Comparison of the density contours at $M_\infty = 2.0$ and $Kn = 0.1$.

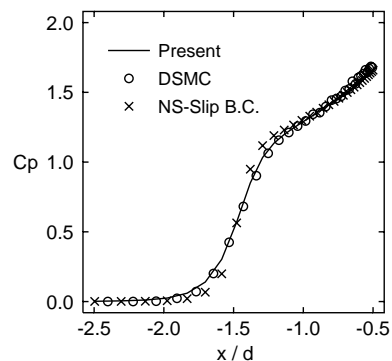


Figure 2: Comparison of pressure along the front stagnation line.

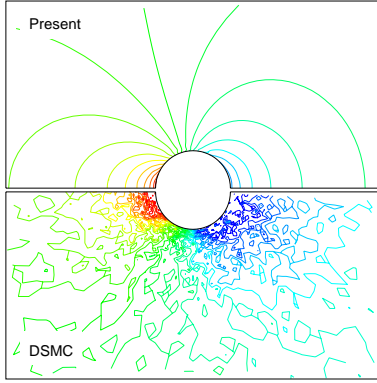


Figure 3: Comparison of the pressure contours obtained at $M_\infty = 0.1$ and $Kn = 0.1$.

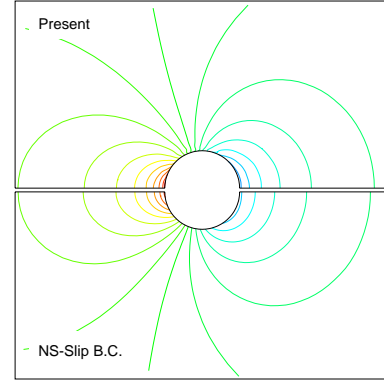


Figure 4: Comparison between the present method and Navier-Stokes with slip boundary conditions at $M_\infty = 0.1$ and $Kn = 0.1$.

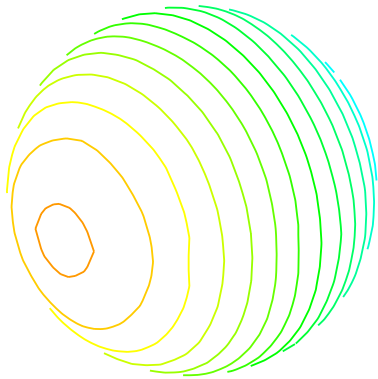


Figure 5: Density contours on a Sphere obtained at $M_\infty = 0.01$ and $Kn = 0.1$.

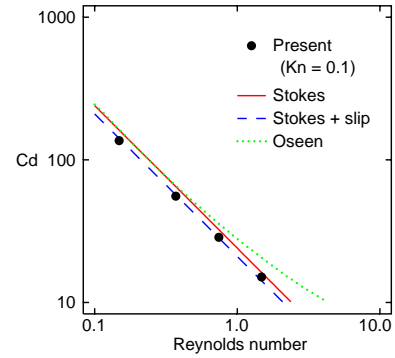


Figure 6: Comparison of the drag coefficient of a sphere.

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