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A Review of Boltzmann-Based CFD Schemes

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There are two distinctive methods in describing the motion of fluid flows mathematically. One is based on the conservation laws of mass, momentum, and energy, and the associated constitutive relations representing the inherent properties of fluid media, which is called the Navier-Stokes-Fourier (NSF) equations in the literature. Another is based on the stochastic partial differential equation of probability distribution of particles in phase space, which is known as the Boltzmann equation [1, 2]. Traditionally, the NSF equations have been considered the de facto mathematical model for virtually all fluid flows and were already validated by extensive theoretical and experimental studies.

Recently, there are, however, rapidly growing interests in computational models based on the Boltzmann equation. Of particular examples are rarefied air flow in high altitude and micro- and nano-scale gas flow in MEMS/NEMS in which the conventional NSF equations are believed to be invalid due to the near-equilibrium assumption introduced in deriving them.

In this study, various Boltzmann-based CFD schemes developed in past decades will be reviewed: the DSMC [3], lattice Boltzmann [4], gas-kinetic scheme, Chapman-Enskog and Burnett, and finally the method of moments [5]. Emphasis will be placed on the key properties of the computational models like treatment of the Boltzmann collision integral, reduction of degree of freedom, incorporation of the conservation laws, and solid wall boundary condition. Also, a critical issue in describing (thermal) non-equilibrium gas flows, the verification and validation (V & V), will be dealt with in detail. In this context, a convergence analysis of the pure-simulation DSMC will be presented. Further, a recent development in the method of moments will be reviewed; for example, a triangular mixed modal discontinuous Galerkin (DG) method based on the conservation laws and non-Newtonian (2^{nd}-order) implicit constitutive models of compressible rarefied and microscale gas [6].

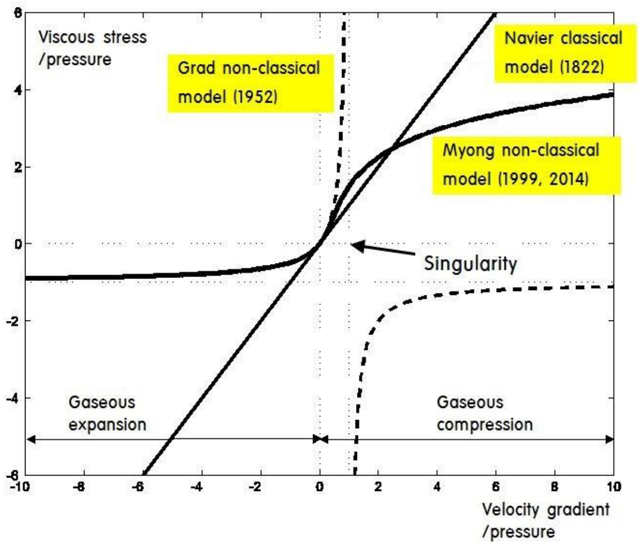

Figure 1 Comparison of classsical and non-classical constitutive relations of a gas.

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