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Supersonic Flows with Nontraditional Transport Described by Kinetic Methods

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Abstract. A new class of supersonic nonequilibrium flows is studied on the basis of solving the Boltzmann and model kinetic equations with the aim to consider new nonlinear structures in open systems and to study anomalous transfer properties in relaxation zones. The Unified Flow Solver is applied for numerical simulations. Simple gases and gases with inner degrees of freedom are considered. The experimental data related to the influence of the so-called optical lattices on the supersonic molecular beams are considered and numerical analysis of the nonequilibrium states obtained on this basis is made. The nonuniform relaxation problem with these distributions is simulated numerically and anomalous transport is confirmed. The conditions for strong changes of the temperature in the anomalous transfer zones are discussed and are realized in computations.

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Key words: The Boltzmann equation, anomalous transport, relaxation zones.

1 Introduction

The thermodynamics of nonequilibrium processes is generally used to study macroscopic transfer phenomena in gases and liquids. The classical transport equations are based on the well-known Navier-Stokes formalism. From the kinetic point of view this formalism is the limit case of the more general kinetic formalism, and if the Knudsen number is not small then the ordinary macroscopic relationships can be invalid (the irreversible thermodynamics can be invalid in this case) and for adequate description it is necessary to solve the Boltzmann equation or other kinetic equations. There are some physical effects intrinsic to the kinetic processes: thermodiffusion, thermoforesis etc (see, e.g., [1]). But

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we will consider effects differing from these phenomena based on the gradients of some quantities. In contrast to these processes the transport processes under consideration are realized because of the dissipation in the boundary and this dissipation is caused by the strong nonequilibrium. In these problems of the nonequilibrium supersonic nonuniform relaxation the boundary nonequilibrium distribution for the supersonic flow forms the gradient of the distribution function (and consequently the macroscopic parameters) downstream. Transport properties of monatomic one-component gases in the spatial nonuniform relaxation zones have been subject to research in [2,3]. The mixtures of simple gases and gases with inner degrees of freedom have been studied for these problems in [4]. The anomalous (from the traditional viewpoint) irreversible transfer of momentum and energy in the scale of the mean free path has been obtained. Namely, in 1D flow the signs of the velocity gradient and the appropriate component of the nonequilibrium stress tensor are the same as well as the signs of the temperature gradient and the heat flux. The special method of expanding in the powers of a small parameter permits to derive the closed form of the transport equations with the mentioned anomalous properties. It is important to note that for supersonic flows the known approach of expansion in powers of inverse Mach numbers $1/M$ does not provide this effect which is due to taking into account the differences of expansion for each molecular velocity.

Numerical results are obtained with the Unified Flow Solver (UFS) [5] for the Boltzmann equation and for some model kinetic equations (of the BGK-type) describing, in particular, molecular (with inner energy) one-component and multi-component gases. The approach applied in the present papers is the direct methods for solving the Boltzmann equation and model kinetic relaxation equations (details are given in [4]). We can also notice the other approaches for solving kinetic equations. The most popular approach is DSMC method which has been elaborated by Bird and the other authors (see [6]). We developed the approach of the direct numerical solving the Boltzmann equation and from our point of view it provides reliable results for the problems under consideration. This approach and the DSMC method possess advantages and disadvantages in kinetic theory (see, e.g., in [2]). We can only mention the approximated approaches, such as kinetic models with small numbers of discrete velocities (Broadwell etc). The very popular Lattice Boltzmann Method (LBM) can be applied, strictly speaking, to slow near equilibrium flows.

The formulation of the nonuniform relaxation problem for 2D case is similar to one for the supersonic free jet but with nonequilibrium boundary conditions in the orifice. The obtained anomalous terms induce the search for the non-traditional transport in numerical calculations. In the present paper we pay the attention to the possibility of experimental testing the effects. For this purpose the numerical simulation for nonequilibrium distributions obtained after modelling the electrical forces of the optical lattice are performed. For goal of the experimental physical measurement it is important to have large changes of macroparameters in the zone of the anomalous transport. Calculations on the basis of the Boltzmann equation with strong nonequilibrium boundary dissipation and large changes of mentioned values are also performed.