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Kinetic theory of transport processes in partially ionized reactive plasma, I: General transport equations

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HIGHLIGHTS

- We consider multicomponent partially ionized plasma in a magnetic field.
- We account for both elastic, inelastic and chemical interactions of particles.
- Using the Grad's method, we obtain the system of transport equations for plasma.
- We discuss further applications of the obtained system of transport equations.

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ABSTRACT

In this paper we derive the set of general transport equations for multicomponent partially ionized reactive plasma in the presence of electric and magnetic fields taking into account the internal degrees of freedom and electronic excitation of plasma particles. Our starting point is a generalized Boltzmann equation with the collision integral in the Wang-Chang and Uhlenbeck form and a reactive collision integral. We obtain a set of conservation equations for such plasma and employ a linearized variant of Grad's moment method to derive the system of moment (or transport) equations for the plasma species nonequilibrium parameters. Full and reduced transport equations, resulting from the linearized system of moment equations, are presented, which can be used to obtain transport relations and expressions for transport coefficients of electrons and heavy plasma particles (molecules, atoms and ions) in partially ionized reactive plasma.

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1. Introduction

Modeling of nonequilibrium processes occurring in the multicomponent partially ionized plasma in the presence of electric and magnetic fields is a crucial task when developing and optimizing different gas discharge devices that use low-temperature plasma. This problem is also important for analysis of phenomena taking place in the boundary layer of spacecrafts entering planetary atmospheres at hypersonic velocities, and investigation of processes in ionospheric and cosmic plasmas.

Partially ionized plasma is characterized by a large variety of chemical and physical processes because it contains a considerable amount of neutral particles, molecules and atoms, the rotational, vibrational and electronic levels of which become excited during the particle interactions. Herein the processes of resonant charge exchange of ions on atoms, dissociation of molecules and ionization of atoms and molecules by electron and heavy-particle impact, three-body

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recombination, associative ionization and other processes, involving inelastic collisions and chemical reactions, play an important role.

The kinetic theory of transport phenomena in the multicomponent gas mixtures and partially ionized plasma was developed by many authors. It is sufficient to mention the classic monographs and reviews [1–4], in which the transport theory was developed on the basis of the Chapman–Enskog method of solution of the kinetic equation. Although the method itself was initially developed for the gas mixtures consisting of monatomic particles that have no internal degrees of freedom, it was later adapted to analysis of transport processes in the mixtures of polyatomic gases [5–10]. For the partially ionized gases the Chapman–Enskog method was also applied primarily for plasma, the particles of which have no internal structure [11–15]. An attempt to generalize the Chapman–Enskog method for analysis of transport phenomena in partially ionized gas mixtures with account for the dissociation reaction of molecules, ionization of atoms and the reverse recombination processes was made in Ref. [16] for the first time. In subsequent years the generalized Chapman–Enskog method was used primarily for analysis of transport processes in gas mixtures with chemical reactions such as bimolecular and dissociation reactions (see the review of these papers in the books [17–19]). Only in the last two decades a series of papers devoted to the transport phenomena theory in the chemically reactive partially ionized plasma appeared. In so doing the general transport relations and the expressions for transport coefficients in partially ionized reactive gas mixtures in a magnetic field were obtained in Refs. [20–22]. In Ref. [23] the transport theory in partially ionized plasma with account for bimolecular reactions, as well as reactions, involving three particles (ionization and recombination), was developed.

Another method, that is alternative to the Chapman–Enskog method in the kinetic theory of gases and gas mixtures, is the Grad's moment method [24]. This method was applied to analysis of the transport processes in monatomic and polyatomic gas mixtures [25–29] and in fully ionized [30,31] and partially ionized plasmas [32–35]. The primary advantages of the moment method are revealed the most when it is used with respect to the multicomponent mixtures and plasmas [34,36]. Grad's moment method was also used for investigation of transport processes in mixtures of chemically reacting gases with bimolecular reactions [37,38] and in a dissociating gas [39].

In the present work the generalized linearized moment method is applied to obtain a system of transport equations for multicomponent reactive partially ionized plasma, the particles of which have internal degrees of freedom. Our paper is organized as follows. The generalized Boltzmann equation, taken as the basis of the present work, and also the most general relations, following from this equation, like the mass, momentum and energy conservation equations for a single plasma component and plasma as a whole, are presented in Section 2. The choice of a zeroth-order approximation to the distribution function of plasma particles is justified and the linearized kinetic equation is discussed in Section 3. The linearized system of moment equations derived on the basis of the Grad's method is presented in Section 4. In Section 5 linear transport relations for scalar, vector and tensorial nonequilibrium parameters of the partially ionized reactive plasma in a magnetic field, obtained from the general system of moment equations, are presented.

2. Conservation equations

We consider the multicomponent partially ionized reactive plasma, which comprises electrons, ions, excited atoms and molecules, possessing internal degrees of freedom. The state of such plasma can be described by a distribution function for particles of species α in the ith quantum state,

$$f_{\alpha i} = f_\alpha\left(\mathbf{v}_\alpha, \mathbf{r}, t, i\right), \tag{2.1}$$

where $\mathbf{v}_\alpha$ is the particle velocity, $\mathbf{r}$ is its coordinate, t is time, i is the generalized index subdivided into indices $i_1, i_2, \ldots$, where the population $\{i_\nu\}$ meets the requirements of a full set of quantum numbers for the ν-th internal modes corresponding to the rotational, vibrational and electronic degrees of freedom of plasma particles.

Evolution of the distribution function $f_{\alpha i}$ in space and time is described by the generalized Boltzmann kinetic equation [4,16,23]:

$$\frac{\partial f_{\alpha i}}{\partial t} + (\mathbf{v}_\alpha \cdot \nabla) f_{\alpha i} + \left(\frac{\mathbf{F}_\alpha}{m_\alpha} \cdot \nabla_{\mathbf{v}}\right) f_{\alpha i} = \sum_\beta \sum_{jkl} J_{ij}^{kl}\left(f_{\alpha i}, f_{1\beta j}\right) + J_{\alpha i}^{r}, \tag{2.2}$$

where ∇ and ∇_v denote the divergence operators in the Cartesian coordinates expressed in terms of space and velocity variables and $\mathbf{F}_\alpha$ is the force acting on a particle of species α with mass m_α, determined in the general case as

$$\mathbf{F}_\alpha = e_\alpha\left(\mathbf{E} + \mathbf{v}_\alpha \times \mathbf{B}\right) + \mathbf{X}_\alpha. \tag{2.3}$$

Here **E** and **B** are electric and magnetic fields, e_α is the particle charge (for electrons we have $e_\alpha = -e$), $\mathbf{X}_\alpha$ is a force of a non-electromagnetic nature.

The binary collision integral J_{ij}^{kl}, written in the Wang Chang and Uhlenbeck form, is as follows [5]:

$$J_{ij}^{kl}\left(f_{\alpha i}, f_{1\beta j}\right) = \int\int\left(\frac{s_{\alpha i}s_{1\beta j}}{s_{\alpha k}s_{1\beta l}} f'_{\alpha k} f'_{1\beta l} - f_{\alpha i} f_{1\beta j}\right) g\sigma_{\alpha\beta}\left(ij\,|kl, g, \chi\right) \mathrm{d}\Omega \mathrm{d}\mathbf{v}_{1\beta}, \tag{2.4}$$

where the primes serve to mark the velocity vectors after the collision, the subscript index "1" is introduced to differentiate the colliding particles when $\alpha = \beta$, $s_{\alpha i}$ is the degeneracy of the ith quantum state of particles of species α, $\sigma_{\alpha\beta}\left(ij\,|kl, g, \chi\right)$

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