INVESTIGATION OF KINETICS OF POPULATIONS OF EXCITED ARGON LEVELS IN A RECOMBINING PLASMA

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INTRODUCTION

A thorough investigation of electron–ion recombination requires not only a study of the macrocharacteristic of this process – the ion–recombination rate constant – but also fuller data on the kinetics of the populations of the individual excited electronic states of the atom. Several of the investigations devoted to solution of the level problem for recombining plasmas of different composition with a view to the possible obtainment of an inverse population of excited electronic levels of atoms are thoroughly analyzed in the review paper [1]. We can mention the experimentally established existence of ionization and temperature nonequilibrium in an expanding plasma, as in [2]. It is of interest to investigate the relaxation of the excited atomic levels. The present paper is devoted to a theoretical and experimental investigation of the recombination of an argon plasma, heated in a reflected shock wave, during its gasdynamic expansion in a nozzle. The calculation of the nonequilibrium flow in the nozzle took into account the relaxation of seven excited levels of argon atoms, and the kinetics of the electrons and electron energy. In the calculations we determined the absorption coefficient of the continuous and discrete spectrum in the infrared region. For the experimental investigation of the nonequilibrium flow we used a shock tube, and the argon was heated by the reflected shock wave. We measured the absorption coefficient of argon along the nozzle at the wavelength \( \lambda = 3.39 \mu \) of a helium–neon laser. We compared the measured and calculated values of the absorption coefficients.

1. The solution of the level problem requires a thorough investigation of the microscopic processes occurring in a plasma which is not in a state of local thermodynamic equilibrium. To determine the populations of the excited states we have to solve a system of differential equations representing all the collisional and radiative processes.

In constructing the equations we make the following assumptions: 1) The flow in the nozzle is uniform; 2) the effects of viscosity, heat conduction, and diffusion can be ignored; 3) heavy particles and electrons have Maxwellian velocity distributions, each with its own temperature; 4) there are no external electric or magnetic fields; 5) the plasma consists of neutral atoms, singly charged ions, and electrons, and is neutral on the whole; 6) photionization and photorecombination can be neglected; 7) only collisional transitions between adjacent levels need to be considered.

Adopting these assumptions we investigated the kinetics of the populations of seven lower excited states of the argon atom. We considered three types of processes: ionization of atoms from excited states by collision with electrons, stepwise excitation of atoms by electrons, and radiative deexcitation of the excited levels. In the calculation of the populations the fine structure of the levels was taken into account only in the aggregate statistical weight of each level. The complete system of elementary processes included 35 reactions occurring in both directions.

The complete system of equations representing the steady flow of a nonequilibrium gas in a nozzle consists of two groups. The first group consists of the gasdynamic equations of continuity, momentum, and energy:

\[
\rho v S = j = \text{const}, \quad \rho v \frac{dv}{dx} = -\frac{dp}{dx} - \frac{H}{\mu} + \frac{1}{2} v^2 = \text{const}
\]  

(1.1)

In these equations \( \rho, v, p, \mu, \) and \( H \) are the density, velocity, pressure, molecular weight, and molar enthalpy, respectively, \( S \) is the cross-sectional area of the nozzle, which depends on the coordinate along the flow, and \( j \) is the mass flow rate in the nozzle. To these equations we add the equation of state of an ionized gas:


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Fig. 1

\[ p = nkT + n_e kT_e \]  
(1.2)

where \( k \) is the Boltzmann constant; \( n \) and \( n_e \) are the densities of heavy particles and electrons; and \( T \) and \( T_e \) are the temperatures of heavy particles and electrons.

The second group consists of the equation for the enthalpy of unit mass, expressed in terms of the molar enthalpies \( H_i \) of the individual components (\( N \) is the total number of components), and the system of kinetic equations representing the relaxation of excited argon atoms and ions, and also the relaxation of the electron energy

\[ \frac{\gamma_i}{\mu} = \sum_{i=1}^{N} \gamma_i H_i, \quad \gamma_i = \frac{n_i}{n_e} \frac{\rho}{\rho_0} \]  
(1.3)

\[ \frac{d\gamma_i}{dt} = W_i, \quad \frac{d\gamma_e}{dt} = W_e \]  
(1.4)

\[ \frac{d\gamma_k}{dt} = W_k, \quad \gamma_k = \frac{E_i - E_0}{n_k T_0} \frac{\rho}{\rho_0} \]  
(1.5)

In these expressions we use the relative equivalent concentrations of the components \( \gamma_i \) (\( n_i \) is the number of particles of the \( i \)-th kind per \( \text{cm}^3 \); \( n_e \) and \( \rho_0 \) are the total particle density and the density of gas in the receiver) and the corresponding quantity \( \gamma_e \) for representation of the electron energy, where \( E_e \) is the electron energy per unit volume (1 \( \text{cm}^3 \)), and \( T_0 \) is the temperature of the gas in the receiver. In Eqs. (1.4), the values of the subscript \( k = 1, 2, \ldots, 7 \) represent the concentrations of argon atoms in the excited states \( 4s, 4p, 3d, 5s, 5p, 4d, \) and \( 6s \), respectively. The expressions for the reaction rates \( W_i \), of the particles were taken from [1] in the corresponding dimensionless form. In the expression for the rate of change of the electron energy \( W_e \) we took into account the transfer of energy between electrons and heavy particles (atoms and ions), and also the heating of electrons by the energy released by ion recombination. The ionization and excitation rate constants were calculated from the formulas given in [3], and the data for radiative deexcitation of the excited states were taken from [4]. The rate constants of the opposite processes were calculated on the basis of the values of the initial rate constants and the equilibrium constants of the reactions. The electron temperature \( T_e \) was found from the calculated electron energy per unit volume \( E_e = (3/2) n_e k T_e \). The electron density \( n_e \) was found from the condition for electrical neutrality of the plasma and the density of atoms in the ground state from the balance of the total number of atoms. From the solution of the whole set of equations we calculated the distribution of all the quantities along the nozzle.

2. The system of equations of nonequilibrium flow in the nozzle was integrated numerically by the use of an implicit difference scheme.

An appropriate choice of gas flow rate ensured passage through the critical flow point. We took into account the nonequilibrium of the flow in both the supersonic and subsonic regions of the nozzle.

For the investigation we selected temperatures and pressure in the nozzle forechamber which could be attained in experiments in which the gas is heated by a shock wave in a shock tube. This corresponded to an