THREE-CHAMBER HEATED SHOCK TUBE FOR INVESTIGATING A HIGH-ENTHALPY DENSE PLASMA

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Investigation of a dense plasma is of interest primarily because there is not strict theory describing its thermodynamic, transport, and optical properties. A considerable number of experimental studies involving detailed investigations of the thermophysical properties of a dense plasma of different chemical elements up to charged particle densities of $n_e \leq 10^{25}$ m^{-3} are now available. At large densities there is only one paper describing detailed investigations. This situation stems mainly from the difficulty of making a dense plasma generator for investigations over a wide range of parameters.

The present paper proposed a three-chamber pneumatic heated shock tube as a dense plasma generator. The advantage of multidiaphragm shock tubes for obtaining high-intensity shock waves, compared with a two-chamber shock tube is pointed out in [1]. A three-chamber shock tube without heating of the walls is described in [2]. Heating of the tube walls leads to a considerable increase of the shock wave intensity [3]. The possibility of a three-chamber pneumatic shock tube to obtain a dense plasma was described in [3] in the example of calculating the parameters of xenon plasma behind the reflected shock.

The layout of the three-chamber tube is shown in Fig. 1. The shock tube 2 consists of three sections: the LPC, the IPC, and the HPC — the low pressure, intermediate pressure, and high pressure chambers, respectively. The tube is placed in the heater 1. The sections are separated from each other by diaphragms. The HPC contains driver gas (helium), and the LPC is filled with the test gas (xenon). The pressure of the gas (helium) in the IPC is chosen to be the geometric mean of the pressures in the HPC and the LPC. The facility operated as follows. After the diaphragm separating the HPC and the IPC is burst, a shock wave propagates in the IPC, and this wave reaches the second diaphragm (between the IPC and the LPC) and reflects from it. The second diaphragm ruptures under the influence of the gas pressure behind the reflected shock, and the shock wave is propagated into the test gas in the LPC.

To calculate the xenon plasma parameters in the three-chamber heated shock tube we simultaneously solve the gasdynamic equations [1] and the thermodynamic equations in the framework of Debye theory in a large canonical ensemble [4]:

$$\frac{p_8}{p_6} = \left\{\frac{2\gamma_6}{\gamma_6+1}M_6^2 - \frac{\gamma_6-1}{\gamma_6+1}\right\}\left\{1-\left(\frac{\gamma_8-1}{\gamma_6+1}\right)\left(\frac{M_6^2-1}{M_6}\right)\right\}^{-\frac{2\gamma_8}{\gamma_8-1}}; \quad (1)$$

$$\frac{p_4}{p_6} = \left\{\frac{2\gamma_6}{\gamma_6+1}M_6^2 - \frac{\gamma_6-1}{\gamma_6+1}\right\}\left\{\frac{(3\gamma_6-1)M_6^2-2(\gamma_6-1)}{(\gamma_6-1)M_6^2+2}\right\}; \quad (2)$$

$$\frac{T_4}{T_6} = \frac{\{(3\gamma_6-1)M_6^2-2(\gamma_6-1)\}\{2(\gamma_6-1)M_6^2+(3-\gamma_6)\}}{(\gamma_6+1)^2M_6^2}, \quad p_6=\sqrt{p_8p_0}; \quad (3)$$

$$\frac{p_4}{p_0} = \left[1+\gamma_0M_0^2\left(1-\frac{\rho_0}{\rho_1}\right)\right]\left[1-\frac{\gamma_4-1}{2}\frac{a_0}{a_4}M_0\left(1-\frac{\rho_0}{\rho_1}\right)\right]^{-\frac{2\gamma_4}{\gamma_4-1}}; \quad (4)$$

$$H_1 = H_0 + \frac{1}{2}U^2\left[1-\left(\frac{\rho_0}{\rho_1}\right)^2\right]; \quad (5)$$

$$p_1 = p_0 + \rho_0U^2\left(1-\frac{\rho_0}{\rho_1}\right); \quad (6)$$

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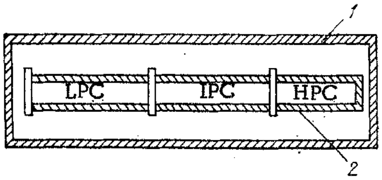

Fig. 1

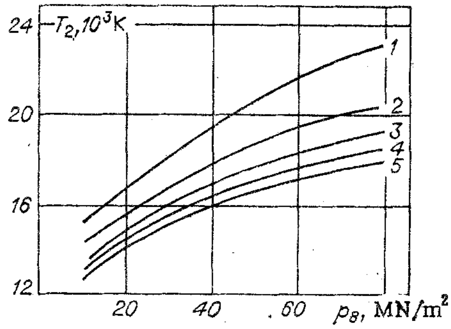

Fig. 2

$$H_2 = H_1 + \frac{1}{2} \frac{\left(1-\frac{\rho_0}{\rho_1}\right)^2 \left(1+\frac{\rho_1}{\rho_2}\right)}{1-\frac{\rho_1}{\rho_2}} U^2; \tag{7}$$

$$p_2 = p_1 + \rho_1 U^2 \left[\frac{\left(1-\frac{\rho_0}{\rho_1}\right)^2}{1-\frac{\rho_1}{\rho_2}}\right]; \tag{8}$$

$$p = n_a kT + 2kTn_e \left\{\alpha^2\left(\frac{2}{\Gamma}\right) + \left(\frac{\Gamma}{3}\right)\alpha^3\left(\frac{2}{\Gamma}\right)\right\}, \tag{9}$$

where $\alpha(2/\Gamma)$ is the positive root of the equation $\alpha^3 + x\alpha^2 - x = 0$, $x = 2/\Gamma$;

$$H = \frac{5}{2} kT(2n_e + n_a) + \frac{kT^2 n_a}{Q_a}\frac{\partial Q_a}{\partial T} + n_e I - 8kT\left(1 - \alpha^2 - \frac{\Gamma}{3}\alpha^3\right); \tag{10}$$

and the atomic statistical sums Q_a are calculated with allowance for reduction of the ionization potential

$$Q_a = \sum_n g_n e^{-E_n/kT}, \quad \frac{E_n}{kT} < \left(\frac{I}{kT} - \frac{\Delta I}{kT}\right),$$

$$\Delta I = \Delta\mu_a - \Delta\mu_e - \Delta\mu_i, \quad \frac{n_e n_i}{n_a} = \frac{2Q_i}{Q_a}\lambda_e^{-3}\exp\left(-\frac{I}{kT} + \frac{\Delta I}{kT}\right). \tag{11}$$

Here p_8, p_6, p_0 are the initial gas pressures in the HPC, IPC and LPC, respectively; γ_8, γ_6, γ_0, M_6, M_0 are the adiabatic indices of the gases and the shock wave Mach numbers; γ_4, p_4, T_4 are the adiabatic index, the pressure and the temperature of the gas behind the reflected shock in the IPC; a_c, a_4 are the sound speeds in the gases; U is the incident shock speed in the LPC; ρ_0, ρ_1, ρ are the initial gas density and the plasma densities behind the incident and reflected shock waves in the LPC; H_0, H_1, p_1, p_2 are the initial gas enthalpy, and the enthalpies and pressures of the plasma behind the incident and reflected shock waves; n_e, n_a are the electron and atom densities; Q_i, Q_a are the statistical sums of the ions and atoms; T is the plasma temperature; $\Gamma = e^2/(kTr_D)$ is the nonideal parameter; I, ΔI are the ionization potential of the atom and the reduction of the ionization potential in the Saha equation; and λ_e is the Debye wavelength of the electron.

The shock wave intensity in the LPC was varied by changing the working gas pressure: p_0 = 0.0098; 0.0196; 0.0294; 0.0392; 0.049 MPa, and the driver gas pressure p_8 = 9.8-78.4 MPa. The initial heating temperature of all three shock tube sections was assumed to be the same (T = 873°K).

Equations (1)-(11) were solved simultaneously on a type BÉSM-6 computer.

Figures 2-6 show the calculated parameters of a dense xenon plasma behind the reflected shock wave. Figure 2 shows the plasma temperature behind the reflected shock wave for different initial xenon pressures in the LPC: Curve 1) p_0 = 0.0098; 2) 0.0196; 3) 0.0294; 4) 0.0392; 5) 0.049 MPa. The plasma parameters behind the reflected shock wave are as follows: Fig. 3 — pressure p_2; Fig. 2 — electron density n_e; Fig. 5 — non-ideal parameter Γ; Fig. 6 — degree of ionization of the plasma. The range of the plasma parameters is: T = (1.3-2.5)$\cdot 10^4$°K; p_2 = 6.86-53.9 MPa; n_e = (0.55-6.5)$\cdot 10^{25}$ m^{-3}; Γ = 0.58-1; α = 0.09-0.5 is the degree of ionization. The range of the shock wave Mach number was M_2 = 6-13. One should

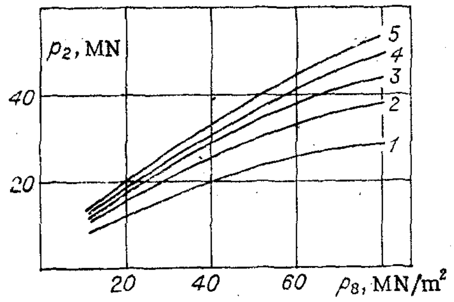

Fig. 3

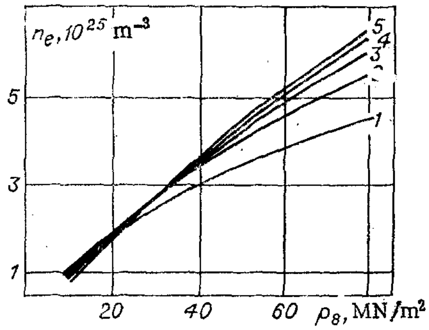

Fig. 4

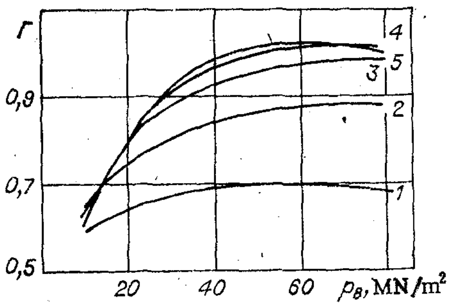

Fig. 5

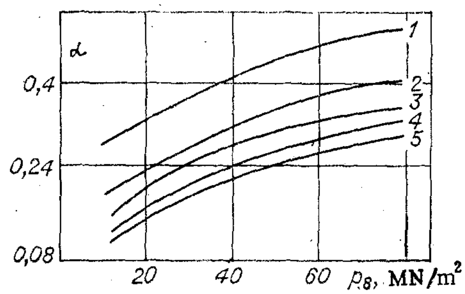

Fig. 6

note the monotonic increase of all the parameters (except the nonideal parameter) over the entire range of increase of shock wave strength. The nonideal parameter increased for variation of driver gas pressure up to $p_s \leqslant 39.2$ MPa, and remained practically constant for larger pressures. On this facility we investigated the thermodynamic and optical properties of a dense xenon plasma up to electron densities of $n_e \simeq 4 \cdot 10^{25}$ m^{-3} [5]. The results of this calculation agreed closely with the experimental results, which indicates that one can make predictions, based on the calculated parameters of a plasma of other chemical elements. The heated three-chamber pneumatic shock tube is a convenient instrument for investigating a dense plasma of various chemical elements over a wide range of the parameters, and including alkali metals and their mixtures with inert gases.

LITERATURE CITED

1. B. Henshall, "The use of a multi-diaphragm scheme in a shock tube," in: Shock Tubes [Russian translation], Inostr. Lit., Moscow (1962).
2. A. A. Kon'kov, A. P. Razin, and A. I. Sokolov, "A two-diagraphm shock tube for obtaining a dense thermal plasma," Teplofiz. Vysok. Temp., 12, No. 4 (1974).
3. A. Gaydon and I. Hurle, The Shock Tube in High-Temperature Chemical Physics [Russian translation], Mir, Moscow (1966).
4. L. P. Kadanoff and G. Baym, Quantum Statistical Mechanics, W. A. Benjamin (1962).
5. V. A. Sechenov, "Investigation of the optical properties of a dense xenon plasma," Fiz. Plazmy, 7, No. 5 (1981).