Generation mechanism of precursor electrons ahead of a hypersonic shock wave in argon

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Abstract

The purpose of the research is to clarify the generation mechanism of precursor electrons ahead of a hypersonic shock wave in argon. The triple-probe measurements and radiation measurements are carried out using a hypersonic shock tube. Theoretical analysis is also carried out using a one-dimensional photoionization model. The triple-probe measurements show that the electron temperature is almost uniform ahead of the shock wave and ranges from 5000 to 11000 K. In contrast to the electron temperature, the electron density increases exponentially as approaching the shock wave and lies between 10^{15} and 10^{17} m^{-3} . These results show that considerable electrons exist in the region ahead of the shock wave. From the radiation measurements, argon ions are found to emit radiation in the region ahead of the shock wave, showing that argon ions are generated from argon atoms by photoionization. The behavior of electron temperature and density is well accounted for by the one-dimensional photoionization model with an assumption of photoionization as the primary ionization process ahead of the shock wave. In conclusion, precursor electrons are mainly generated by photoionization, making use of the radiation energy behind the shock wave.

Key words : Shock wave, Precursor electrons, Electron temperature, Electron density, Triple-probe method

1. Introduction

Recently, various planetary explorations have been proposed around the world. Now, astronauts are staying in the international space station (ISS) and conducting various space activities. In addition, NASA has a plan to send humans to Mars in the 2030s. Improvement of atmospheric entry flight technology is an important goal to realize these missions. When a space vehicle enters into a planetary atmosphere, a detached shock wave is generated around the body, resulting in the severe aerodynamic heating. The aerodynamic heating is affected by the nonequilibrium processes of thermal relaxation, dissociation, ionization and recombination reactions around space vehicles (Park, 1985). An accurate prediction of the thermochemical nonequilibrium phenomena is necessary for the development of a thermal protection system (TPS). Now, the evaluation of flight environments is carried out by computational fluid dynamics (CFD) simulations (Gnoffo, et al, 1989). The result highly depends on the accuracy of the thermochemical model applied in the simulation. Therefore, the model should be validated and updated to improve the accuracy.

Yamada et al. (2012a, 2012b) conducted shock tube experiments in super-orbital entry flight conditions to validate the two-temperature model (Park, 1988, 1989, 1990, 1993) which was widely used to evaluate entry flight environments. The results show that the relaxation process of the electronic excitation mode is much different from the model prediction. To clarify this problem, a numerical analysis was carried out by considering the nonequilibrium process of the electronic excitation mode (Yamada, et al., 2013). It was found that the calculated relaxation process agreed well with the measured one by assuming the generation of electrons ahead of a shock wave. The existence of precursor electrons ahead of shock waves in N_2 was confirmed by the triple-probe measurements using a shock tube (Fujita, et al., 2001a, 2001b). In addition, the effect of precursor electrons on the thermochemical nonequilibrium process behind shock waves was numerically

analyzed (Scott and Leland, 1992). In these studies, N_2 and air were considered as ambient gases. Therefore, the clarification of the phenomena associated with precursor electrons is considered to be complex because the energy modes of molecules are much more than those of atoms (Anderson, 2006). This fact suggests that the use of atomic gas is desirable for the first stage of the clarification. In 1960s, the generation mechanism of precursor electrons was investigated using argon as the ambient gas (Weymann, 1960, 1969; Holmes and Weymann, 1969). These results pointed out that electron diffusion and photoionization were possible candidate to generate precursor electrons ahead of shock waves in argon. However, the generation mechanism of precursor electrons has not been yet clarified.

The purpose of the present study is to clarify the generation mechanism of precursor electrons ahead of a shock wave in argon. The triple-probe method and theoretical analysis by a one-dimensional photoionization model in previous works (Fujita, et al., 2001a, 2001b) are applied for argon in this study. In addition, radiation measurements are newly conducted in the region ahead of the shock wave for further clarification.

In the following, the experimental facility and the method are explained in Section 2. The theory of the one-dimensional photoionization model is described in Section 3. Section 4 presents the results and discussion. Finally, the conclusion of the present study is shown in Section 5.

Nomenclature

c : speed of light, m/s

e : elementary charge, 1.9×10^{-19} C

h : plank constant, 6.626×10^{-34} J·s

k_B : Boltzmann constant, 1.380622×10^{-23} J/K

m_e : the mass of electrons, 9.109×10^{-31} kg

m_i : the mass of argon ions, 6.642×10^{-23} kg

P_0 : test gas pressure, Pa

T_e : the electron temperature, K

T_i : the ion temperature, K

V_{sh} : shock velocity, km/s

ν : frequency, s^{-1}

2. Experimental facility and method

2.1 Shock tube facility

Hypersonic shock waves are generated in argon using a free piston-driven shock tube at Tottori University, which can simulate a shock wave formed in typical planetary entry flights (Yamada, et al., 2013). The test section with a 44 mm square cross section is made of aluminum alloy to reduce the emissions caused by impurities, mostly due to iron (Park, 1993). Four observation windows with a diameter of 30 mm are mounted on the test section wall. The test section is evacuated to the pressure of 3.0 Pa by a roots pump (EDARDS, QMB500) backed up by an oil rotary pump (EDWARDS, E2M80) before filling a test gas.

2.2 Measurement system

2.2.1 Optical measurement system

Figure 1 shows a schematic drawing of the spectroscopic measurement system at the test section. The shock velocity at the test section is measured by the double-laser schlieren measurement system (Yamada, et al., 2011). Two laser beams are aligned along the flow direction in line to pass through the test section perpendicularly to the axis of the shock-tube flow. The optical path is adjusted to arrive at separate avalanche photodiodes (APD) using flat mirrors. Deflection of the laser beams as a result of a density gradient at the shock front causes a change in the output signals of avalanche photodiodes. The shock velocity at the test section can be obtained from the beam distance and the time difference of the output changes.

Radiation measurements around the shock wave are conducted by a time-resolved emission spectroscopy (Yamada, et al., 2012). This technique provides the evolution of the radiation at fixed wavelength as a function of time. The

measurement system consists of a quartz convex lens, a monochromator (JASCO, CT-25C), and a photomultiplier tube (PMT) (Hamamatsu, R928). The radiation from the measurement point in the central axis is focused on the entrance slit of the monochromator and dispersed into its spectral components. The time-resolved radiation at fixed wavelength is recorded by a digital oscilloscope (Agilent Technologies, DSOX2024A). The measured radiation data can be correlated with the shock front and converted into the spatially-resolved radiation data using a schlieren signal and measured shock velocity.

Fig. 1 Spectroscopic Measurement System

Fig. 2 Triple-Probe Measurement System

Fig. 3 Electric circuit of the triple-probe

2.2.2 Triple-probe measurement system

In past studies (Fujita, et al., 2001a, 2001b), the electron density and temperature ahead of shock waves in N₂ were measured by the triple-probe method which enabled us to conduct instantaneous measurements with high time resolution. In this study, we apply this method to the measurements of the electron density and temperature ahead of a shock wave in argon. In the triple-probe method, following assumptions are introduced to the precursor plasma to deduce electron density and temperature from the measured signal: 1) The plasma is electrically quasi-neutral except for the sheath region surrounding the probe, 2) The thermal velocity of electrons and ions is in the Maxwellian distribution, 3) The plasma velocity of the center of gravity is much smaller than the mean thermal velocity of ions and electrons, 4) The sheath thickness is smaller than the mean free path of electrons. Figure 2 shows the experimental setup of the triple-probe measurement system developed at the other side of the spectroscopic measurement system. The plane probe made of copper with a diameter of 2 mm is used for the triple-probe measurement. The surface of the probe is covered with a 50- μ m-thickness insulator sleeve except the tip in order to minimize the influence of the probe potential on the effective capturing area of the probe. Three probes are separately placed at a 5 mm interval and inserted normally to the flow. The tip of the probes is located at 15 mm away from the inner wall to reduce the influence of the wall. Three probes can detect common plasma properties because the plasma properties can be considered to be uniform in the direction normal to the flow.

Figure 3 shows the electric circuit of the triple-probe. In the circuit, E₂ and E₃ are bias voltages between probes. The output voltages for E₂ and E₃ are set as 9.0 and 1.5 V, respectively and powered by dry cell batteries. Electric resistances R₂ and R₃ are set to 15 k Ω , while R₁ is set to 1 M Ω to realize the condition for quasi-isolation of the probe circuit shown in Eq. (1).

$$I_1 + I_2 + I_3 = 0 \quad (1)$$

where I_1 , I_2 , and I_3 are probe currents. The probe voltages are measured by a digital oscilloscope with 1M Ω input impedance and the corresponding probe currents are deduced using Eq. (1). For plasmas having the Maxwellian velocity distribution, the total current running into the individual probe is given by

$$I_j = I_i - I_e \exp\left(\frac{e\phi_j}{k_B T_e}\right) \quad \text{for } j = 1 \text{ to } 3, \quad I_i = \frac{en_e S}{4} \sqrt{\frac{8k_B T_e}{\pi m_i}} \alpha, \quad I_e = \frac{en_e S}{4} \sqrt{\frac{8k_B T_e}{\pi m_e}} \quad (2)$$

where I_i and I_e are the ion current and electron current running into the probes, respectively, n_e is the electron density in the undisturbed plasma, $\alpha = T_i / T_e$ is the parameter, S is the effective capturing area of the probe, and ϕ is the electric potential of the probe measured from the plasma potential. In this study, S is 3.14×10^{-6} m². Because α in Eq. (2) cannot be determined self-consistently in the principle of the triple-probe method due to uncertainties in the ion temperature it is treated as a parameter and assumed to range from 0.01 to 1.0 in the present measurements. The electric potential of the probe is correlated with the measured probe voltage by

$$\phi_j = V_g + V_j \quad \text{for } j = 1 \text{ to } 3 \quad (3)$$

where V_g is the ground potential measured from the plasma potential, V_j is the probe voltage. To apply Eq. (2) to three probes with the substitution of Eq. (3) gives the following simultaneous equations.

$$I_1 = I_i - I_e \exp\left(\frac{e(V_g + V_1)}{k_B T_e}\right) \quad (4)$$

$$I_2 = I_i - I_e \exp\left(\frac{e(V_g + V_2)}{k_B T_e}\right) \quad (5)$$

$$I_3 = I_i - I_e \exp\left(\frac{e(V_g + V_3)}{k_B T_e}\right) \quad (6)$$

To solve the above simultaneous equations by deleting I_i and I_e gives the following Eq. (7)

$$\frac{I_1 - I_2}{I_1 - I_3} = \frac{1 - \exp\left(\frac{e(V_2 - V_1)}{k_B T_e}\right)}{1 - \exp\left(\frac{e(V_3 - V_1)}{k_B T_e}\right)} \quad (7)$$

The electron temperature can be obtained from Eq. (7). On the other hand, to solve the simultaneous equations by deleting I_e gives the following Eq. (8)

$$I_i = \frac{I_3 - I_2 \exp\left(\frac{e(V_3 - V_2)}{k_B T_e}\right)}{1 - \exp\left(\frac{e(V_3 - V_2)}{k_B T_e}\right)} \quad (8)$$

The electron density can be obtained from Eq. (8) by treating α as a parameter.

2.3 Test conditions

In this study, argon is used as a test gas to simplify the phenomena. Nominal shock velocity is 6.12 ± 0.13 km/s and the test gas pressure is 50 Pa. The setting of monochromator for radiation measurements is shown in Table 1. In the radiation measurements, radiations from argon atoms at 763 nm and argon ions at 358 nm are measured with a grating of 1200 groove/mm. The center wavelength varies depending on the targeted radiations for argon atoms and ions. The input slit is set to 50 μ m and exit slit is set to 690 μ m corresponding to the measured wavelength span.

Table 1 Monochromator setting

Features targeted	Center wavelength, nm	Wavelength span, nm	Grating density, groove/mm	Input slit, μ m
Ar II 4p ⁴ D - 4d ⁴ F	358	2	1200	50
Ar I 4s ² [3/2] - 4p ² [3/2]	763	2	1200	50

3. Theory of the one-dimensional photoionization model

To analyze the behavior of precursor electrons ahead of the shock wave, a one-dimensional photoionization model (Fujita, et al., 2001b) is formulated and applied for argon in this study. On the coordinate system fixed with the shock wave, flow properties ahead of the shock wave are regarded as a steady-state flow propagating at a velocity equal to the incident shock velocity. In this case, the mass conservation equation of electrons is given by

$$\frac{\partial [n_e (V_{sh} + V_d)]}{\partial x} = \dot{\omega}_+ - \dot{\omega}_- \quad (9)$$

where x is the coordinate aligned in the flow direction with its origin being located at the shock front. V_d is the mean diffusion velocity of electrons. $\dot{\omega}_+$ and $\dot{\omega}_-$ are the rates of electron production and loss, respectively. If we assume the ambipolar diffusion for electrons from the region behind the shock wave, V_d is expected to be negligibly smaller than V_{sh} . Here, the order of the left hand side of Eq. (9) is estimated to be $10^{20} \text{ m}^{-3} \text{ s}^{-1}$ in the present experimental condition. $\dot{\omega}_-$ is considered to be caused by three-body recombination in the slightly ionized plasma under consideration. The order of $\dot{\omega}_-$ is estimated to be $10^{16} \text{ m}^{-3} \text{ s}^{-1}$ for $n_e = 3.8 \times 10^{16}$, which is observed at a 150-mm distance ahead of the shock wave for $\alpha = 0.01$. Therefore, Eq. (9) can be reduced to be

$$V_{sh} \frac{\partial n_e}{\partial x} = \dot{\omega}_+ \quad (10)$$

The energy conservation equation of electrons is given by

$$\frac{\partial}{\partial x} \left(\frac{3}{2} n_e k_B T_e V_{sh} \right) = e \mu_e E^2 n_e + \frac{3}{2} k_B T_0 \dot{\omega}_+ - \frac{3}{2} k_B T_e \dot{\omega}_- - \frac{3}{2} n_e k_B T_e \kappa_{ea} \nu_{ea} \quad (11)$$

In the right-hand side of Eq. (11), the first term is the energy gained from the electric field, the second term is the energy produced in ionization, the third term is the energy loss due to recombination, and the fourth term is the energy loss due to collisions with heavy particles. Here, μ_e and E in the first term are the mobility and the strength of the electric field, respectively. T_0 in the second term is the mean temperature of electrons produced in ionization. κ_{ea} and ν_{ea} in the fourth term are the energy transfer coefficient and the collision frequency of electrons against neutral species, respectively. For the plasma under consideration, the orders of each term in the right hand side of Eq. (11) are 10^{-1} , 10^2 , 10^{-3} , and 10^1 in this order. The first and the third terms are found to be smaller than the other terms from the order comparison. Therefore, by neglecting these terms and substituting Eq. (10) for $\dot{\omega}_+$, Eq. (11) can be reduced to be

$$\frac{\partial T_e}{\partial x} = (T_0 - T_e) \frac{\partial(\ln n_e)}{\partial x} - \frac{T_e \kappa_{ea} \nu_{ea}}{V_{sh}} \quad (12)$$

where $\kappa_{ea} = 2.74 \times 10^{-5}$, $\nu_{ea} = 8.14 \times 10^7 \text{ s}^{-1}$. In the present analysis, electrons ahead of the shock wave are assumed to be produced by photoionization of argon atoms, making use of the radiation energy emitted from the region behind the shock wave and the photoionization reaction is represented as

For the evaluation of the electron production rate $\dot{\omega}_+$, the following assumptions are introduced for simplicity: 1) One photon produces one electron by the photoionization reaction, 2) Photoexcitation of argon atoms is neglected, 3) Photoabsorption occurs only in the region ahead of the shock wave. In addition, radiation is assumed to be emitted forward one-dimensionally from the shock front. Because the light having sufficient energy to ionize argon atoms (above 15.76 eV) is, in general, optically thick behind the shock wave, such radiation can be regarded as a black body radiation from the shock front. Assuming the black body radiation, the number of photons in the frequency interval between ν and $\nu + d\nu$ per unit solid angle is given at the shock front as

$$I_0(\nu) d\nu = \frac{2\pi}{c^2} \frac{\nu^2}{\exp(h\nu/k_B T_{eq}) - 1} d\nu \quad (14)$$

where T_{eq} is the representative temperature of the black body radiation. Total number of photons capable of ionizing argon atoms is obtained by integrating Eq. (14) from the ionization frequency ν_i of argon atoms and given by

$$q_0 = \int_{\nu_i}^{\infty} I_0(\nu) d\nu \quad (15)$$

Under the condition of $h\nu/k_B T_{eq} \gg 1$ for $\nu > \nu_i$, Eq. (15) can be integrated to a good approximation as

$$q_0 = \frac{2\pi \nu_i^3}{c^2} (\gamma + 2\gamma^2 + 2\gamma^3) \exp(-1/\gamma) \quad (16)$$

where $\gamma = k_B T_{eq} / h\nu_i$. Similarly, the mean temperature of electrons produced in photoionization is given by

$$T_0 = \frac{\int_{\nu_i}^{\infty} h(\nu - \nu_i) I_0(\nu) d\nu}{k_B \int_{\nu_i}^{\infty} I_0(\nu) d\nu} = \frac{1 + 4\gamma + 6\gamma^2}{1 + 2\gamma + 2\gamma^2} T_{eq} \quad (17)$$

Provided that emission is negligible in the region ahead of the shock wave, emitted photons from the shock front are absorbed at the distance x from the shock front according to the radiative transfer equation described by

$$\frac{dq}{dx} = \mu q \quad (18)$$

where μ is the absorption coefficient of photons and defined as

$$\mu = \sigma_P n_{Ar} \quad (19)$$

where σ_P is the photoionization cross section, and n_{Ar} is the number density of argon atoms. According to Ref. (Katurayama, 2007), σ_P is estimated to be $0.34 \text{ \AA}^2$. n_{Ar} is $1.21 \times 10^{22} \text{ m}^{-3}$ for the test gas pressure of 50 Pa and assumed to be constant in this study. The rate of electron production by the photoionization is obtained by integrating Eq. (18) for x and given by

$$\dot{\omega}_+ = \mu q_0 \exp(\mu x) \quad (20)$$

Integration of Eq. (10) with (20) using the boundary condition $n_e \rightarrow 0$ for $x \rightarrow -\infty$ yields

$$n_e = \frac{q_0}{V_{sh}} \exp(\mu x) \quad (21)$$

Substitution of n_e in Eq. (12) with Eq. (21) gives a reduced equation for T_e as

$$\frac{\partial T_e}{\partial x} = \mu(T_0 - T_e) - \frac{T_e \kappa_{ea} V_{ea}}{V_{sh}} \quad (22)$$

Finally, T_e ahead of the shock wave can be obtained by solving Eq. (22) with Eq. (17).

4. Results and Discussion

4.1 Measured Electron Temperature and Density

Figure 4 shows the measured probe voltages as a function of the position relative to the shock front, which are scaled as a negative value in the upstream direction. Probe voltages increase and the difference becomes larger as approaching the shock wave. Figure 5 shows the probe currents obtained using these probe voltages. The probe currents vary drastically as approaching the shock wave.

Figure 6 shows the electron temperature distribution deduced using the measured probe voltages and currents as a solid line. In this figure, circles represent the position where the error bars are evaluated. The electron temperature slightly decreases in the range between 150 and 80 mm ahead of the shock wave and reaches the minimum value of about 7500 K. After the minimum value, the electron temperature increases slightly as approaching the shock wave. The error bars in this figure are estimated from the signal to noise ratio of measured probe voltages. It is noted that the error bars increase as the distance from the shock wave increases due to the decrease of the signal to noise ratio. Considering the error bars, the electron temperature is considered to be almost uniform ahead of the shock wave and lies between 5000 and 11000 K.

Figure 7 shows the electron density distribution deduced using the measured probe voltages, currents, and electron temperature for $\alpha = 0.01, 0.1$, and 1.0 as solid lines. In this figure, circles represent the position where the error bars are evaluated. In the weakly ionized plasma under consideration, the ion temperature is considered to be much lower than the electron temperature, and to be close to the temperature of argon atoms, because the energy exchange between ions and atoms is more frequent than that between ions and electrons. To take this into consideration, the electron density is plotted for $\alpha = 0.01, 0.1$, and 1.0 , corresponding to an increase of the ion temperature in this order. The electron density is found to be less sensitive to α because a decrease of α by the factor of one hundredth increases the electron density only by an order of magnitude. Considering that the electron temperature ranging from 5000 and 11000 K as shown in Fig. 6, while the initial temperature of the ambient argon gas is the room temperature, the practical electron density is considered to lie between two curves produced for $\alpha = 0.01$ and 1.0 . In contrast to the electron temperature distribution, the electron density increases almost exponentially as approaching the shock wave and lies between 10^{15} and 10^{17} m^{-3} .

These results show that precursor electrons exist within a 150 mm distance from the shock wave. There are two possible mechanisms for the generation of precursor electrons. One is electron impact ionization and the other is photoionization. Here, the order of the electron production rate by photoionization is estimated to be $10^{20} \text{ m}^{-3} \text{ s}^{-1}$ at 150 mm ahead of the shock wave using Eq. (20). On the other hand, the order of the electron production rate by electron

impact ionization is estimated to be $10^{17} \text{ m}^{-3} \text{ s}^{-1}$ at 150 mm ahead of the shock wave using the equation in Ref. (Hoffert, et al., 1967). In addition, the mean free path of electrons ahead of the shock wave is on the order of 1 mm. Therefore, photoionization is considered to be dominant to generate precursor electrons from argon atoms ahead of the shock wave.

Fig. 4 Output voltages from the probe circuit

Fig. 5 Probe currents

Fig. 6 Electron temperature distribution

Fig. 7 Electron density distribution

4.2 Measured Radiation Distribution

Radiation measurements are separately conducted by removing the triple-probe measurement system to avoid the influence of probes on the shock tube flow. Figures 8 (a) and (b) show radiation intensity distributions for argon atoms at 763 nm and argon ions at 358 nm, respectively. In Fig. 8 (a), the radiation intensity for argon atoms starts to increase rapidly near the shock front and reach the peak immediately behind the shock wave. After the peak, the radiation intensity rapidly decreases to a plateau. It is found that argon atoms start to emit radiation at around 5 mm ahead of the shock wave. This is due to the electron impact excitation caused by the electrons diffused from the region behind the shock wave.

The radiation profile for argon ions is much different from that for argon atoms as shown in Fig. 8 (b). The radiation intensity for argon ions starts to increase at about 100 mm ahead of the shock wave and becomes higher as approaching the shock wave, showing that argon ions are generated in the region ahead of the shock wave. The radiation intensity reaches the peak at the shock front and rapidly decreases to a plateau behind the shock wave. The increase of the radiation intensity ahead of the shock wave is considered to indicate that argon ion number density increases. On the contrary, the electron density also increases as approaching the shock wave as shown in Fig. 7. The spatial profile of the radiation for argon ions seems to correlate with that of the electron density. If the photoionization is dominant in the region ahead of the shock wave, ions and electrons would be present in equal numbers, indicating that the spatial profiles are same each

other. In addition, the effect of electron diffusion is considered to be smaller than that of photoionization for the electron production in the present experimental condition. This is because electron diffusion from the region behind the shock wave would produce only electrons while photoionization would result in an electrically neutral plasma. In this study, the radiation of argon ions is measured in the precursor region, showing that photoionization occurs. In this case, electron diffusion is considered to be ambipolar diffusion. In the region far from the shock front, the existence of electrons may be difficult by ambipolar diffusion. Therefore, the present result is considered to suggest precursor electrons are mainly generated from argon atoms by the photoionization of Eq. (13).

Fig. 8 Radiation intensity distribution

4.3 Validation of Photoionization Model

In order to verify the photoionization model formulated in the Section 3, the electron temperature is numerically calculated by Eq. (22) for several representative temperatures of the black body radiation T_{eq} and compared with the measured electron temperature in Fig. 9. In this figure, the calculated electron temperatures are represented as dashed lines, while the measured electron temperature is represented as a solid line. In addition, circles represent the position where the error bars are evaluated. The calculated electron temperature is uniform and higher with increasing T_{eq} . Considering error bars, the measured electron temperature is almost uniform as approaching the shock wave and found to be at the same order of magnitude as the calculated one for T_{eq} ranging from 7500 K to 9500 K. Note that the behavior of the electron temperature in the experiment can be well accounted for by Eq. (22), assuming photoionization as the primary ionization process ahead of the shock wave.

The electron density is calculated by Eq. (21) for several representative temperatures of the black body radiation T_{eq} and compared with the measured electron density in Fig. 10. In this figure, the calculated electron densities are represented as dashed lines, while the measured electron densities are represented as solid lines. In addition, circles represent the position where the error bars are evaluated. The calculated electron density increases exponentially as approaching the shock wave and the value is higher with increasing T_{eq} . The measured electron density is found to be at the same order of magnitude as the calculated one for T_{eq} ranging from 8600 K to 9600 K. In addition, the behavior of the measured electron density agrees well with the calculated one. Because of these agreements, precursor electrons ahead of the shock wave in argon are considered to be produced by photoionization. Strictly speaking, the calculated electron density slightly deviates from the measured one. This is because $\dot{\omega}_+$ in Eq. (20) is the simple model in which the radiation transfer is treated as one dimension. In addition, μ in Eq. (19) is assumed to be constant. However, μ is not actually constant but the function of x because n_{Ar} varies as a function of x , corresponding to the photoionization of Eq. (13). If we use an accurate model, $\dot{\omega}_+$ is believed to be different form from Eq. (20).

Fig. 9 Comparison of electron temperature between experiment and calculation

Fig. 10 Comparison of electron density between experiment and calculation

5. Conclusion

In this study, the electron temperature and density distributions are measured in the region ahead of the shock wave in argon by the triple-probe method. In addition, radiation measurements are newly conducted in the region ahead of the shock wave. The triple-probe measurements show that the electron temperature is almost uniform ahead of the shock wave and ranges from 5000 to 11000 K. In contrast to the electron temperature, the electron density increases exponentially as approaching the shock wave and lies between 10^{15} and 10^{17} m^{-3} . From these results, considerable electrons are found to exist in the region ahead of the shock wave. The radiation measurements show that the radiation intensity of argon ions starts to increase at around 100 mm ahead of the shock wave, consisting with the fact that argon ions are generated from argon atoms by photoionization, making use of the radiation energy behind the shock wave. The behavior of the electron temperature and density is well explained qualitatively by the one-dimensional photoionization model with an assumption of photoionization as the primary ionization process ahead of the shock wave.

In conclusion, the dominant generation mechanism of precursor electrons ahead of the shock wave in argon is photoionization, making use of the radiation energy behind the shock wave. In the next step, we will develop the measurement method to obtain electron states around the shock front at a time and improve the accuracy of the thermochemical model by including the generation mechanism of precursor electrons.

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