Ionization of air in flow around a blunt wedge at relatively low hypersonic speeds

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Abstract. Calculations are performed for investigation of air ionization near to surface of blunted wedges with half-angles $\phi = 30^\circ$ and $90^\circ$ and radii of blunting of $R_n = 1.5$ and 2.0 cm, moving at speeds of $3 \div 6$ km/s in an air atmosphere with unperturbed gas parameters corresponding to altitudes of $20 \div 60$ km.

1. Introduction
The movement of hypersonic aircraft leads not only to a strong heating of their constructive elements, but also to ionization of the gas in the compressed layer near the streamlined surface, which is a very important aspect of the hypersonic flight of an aircraft, since it leads to a radio communication disruption. At superorbital velocities of spacecraft returning to Earth ($V_\infty > 9$ km/s) the kinetic energy of the colliding particles proves to be sufficient for direct shock ionization of gas particles. At relatively low hypersonic velocities ($V_\infty < 7$ km/s) the question of the primary cause of the appearance in the gas flow of a significant number of electrons. In a number of computational and theoretical studies [1–6] it was established that the most probable cause of primary ionization is the process of associative ionization, which is at least the two-stage process

$$N + O \rightarrow NO^+ \rightarrow NO^+ + e^-,$$

and at this the atoms N and O appear as a result of the dissociation of air components, i.e. molecular nitrogen and molecular oxygen in a mutual collision. In this case, the dissociation of molecules is often not due just to their collision, but is accompanied by the excitation of internal degrees of freedom, in the first place – the vibrations of nuclei in molecules. Therefore, there is a complex multi-stage nature of this process.

Calculations and experiments [7] showed a high probability of realizing this scenario of ionization development at the surface of the body flying at moderate hypersonic speed. The experiments were performed on a shock tube for the velocities of shock waves in the range $V_\infty = 4.7 \div 6.7$ km/s. These experiments showed a very high intensity of the radiation of a heated air plug behind the front of the shock wave in the region of the vacuum ultraviolet spectrum (wavelength $\lambda \sim 190 \div 220$ nm) was detected, which confirms the appearance of NO molecules in the flow of excited electronic states $A^2\Sigma^+, B^2\Delta, B^2\Pi, C^2\Pi, D^2\Sigma^+$ [8].
Numerical simulation results of the processes of physicochemical kinetics behind the front of the shock wave and the spectral emissivity of the air showed good agreement with the radiation intensity observed in the experiment. The used kinetic model of associative ionization [9], applied in [4,5], showed a high probability of associative ionization.

This is the rationale for choosing a model of physicochemical kinetics for the study of ionization processes at relatively low hypersonic velocities. However, it should be borne in mind that the use of this model at two speeds of experimental hypersonic blunted cones ~ 7.4 km/s [4] and 5.6 km/s [4, 10], has shown the necessity of modifying the rate constants of associative ionization with decreasing velocity.

Thus, the kinetic model underlying the study of ionization processes at the blunt wedge surface is based on the process of associative ionization, which includes the dissociation of $N_2$ and $O_2$ molecules, the formation of NO molecules as a result of chemical reactions (primarily due to collisional association of N and O atoms), the excitation of electronic states of NO* with the subsequent decomposition of NO* into NO$^+$ and e$^-$.

This kinetic model is used in this work to analyze the gas ionization in the vicinity of a blunt wedge in a wide range of velocities $V_\infty = 3\pm 6$ km with the parameters of the incident flow corresponding to altitudes $H = 20\pm 60$ km. Calculations are performed for wedges with half-angles $\varphi = 3^0$ and $9^0$ for two radii of blunting $R_a = 1.5$ and 2.0 cm.

2. Results of numerical simulation of ionization processes in flow past a blunt wedge

The scheme of the problem being solved is shown in figure 1. The matrix of the calculated variants is given in table 1, where in addition to the initial data, the braking temperature is presented.

$$T_0 = T_\infty + \frac{V_\infty^2}{c_p} = T_\infty \left(1 + \frac{\gamma - 1}{2} M_\infty^2\right)$$

Table 1. Initial conditions for the calculations.

| $p_\infty$, erg/cm$^3$ | $\rho_\infty$, g/cm$^3$ | $T_\infty$, K | $V_\infty$, cm/s | $M_\infty$ | $T_0$, K |
|------------------------|------------------------|----------------|-----------------|-------------|----------|
| $H = 20$ km            |                        |                |                 |             |          |
| 55300                  | 0.889 $\times 10^{-4}$ | 217            | $3\times 10^5$  | 11.2        | 4565     |
|                        |                        |                | $4\times 10^5$  | 15          | 7957     |
| $H = 30$ km            |                        |                |                 |             |          |
| 12000                  | 0.184 $\times 10^{-4}$ | 227            | $3\times 10^5$  | 11          | 4564     |
|                        |                        |                | $4\times 10^5$  | 14.6        | 7949     |
| $H = 40$ km            |                        |                |                 |             |          |
| 2870                   | 0.400 $\times 10^{-5}$ | 250            | $3\times 10^5$  | 10.2        | 4591     |
|                        |                        |                | $4\times 10^5$  | 13.9        | 7979     |
|                        |                        |                | $5\times 10^5$  | 17.4        | 12334    |
| $H = 50$ km            |                        |                |                 |             |          |
| 798                    | 0.103 $\times 10^{-5}$ | 271            | $3\times 10^5$  | 10.1        | 4628     |
|                        |                        |                | $4\times 10^5$  | 13.4        | 8029     |
|                        |                        |                | $5\times 10^5$  | 16.8        | 12401    |
| $H = 60$ km            |                        |                |                 |             |          |
| 220                    | 0.310 $\times 10^{-6}$ | 247            | $3\times 10^5$  | 10.2        | 4584     |
|                        |                        |                | $4\times 10^5$  | 14.2        | 7967     |
|                        |                        |                | $5\times 10^5$  | 17.5        | 12318    |

The author's computer code NERAT–2D was used in the calculations. The method of integrating the system of Navier–Stokes equations for the motion of a viscous, heat-conducting, chemically reacting gas is described in detail in [4, 10].
Figures 2–4 show the results of calculations of flow field above a blunted wedge with a half angle \( \phi = 9^\circ \) at a velocity of \( V_\infty = 4 \text{ km/s} \) at a height of \( H = 20 \text{ km} \). We note the characteristic features of gas flow under the indicated conditions.

Figure 2, \( a \) shows the fields of translational temperatures and vibrational temperatures of \( \text{N}_2 \). The greatest values of translational temperature are achieved in the vicinity of the frontal blunting of the wedge. Here the temperature is close to the braking temperature \( \sim 4500 \text{ K} \). It is significant that the vibrational temperature \( \text{N}_2 \) differs markedly from the translational temperature in the near wake, where a flow of rarefaction is realized (see figure 2, \( b \)). In figure 2, \( c \) electron concentration fields are shown for the wedge velocity of \( V_\infty = 4 \text{ km/s} \) at an altitude \( H = 20 \text{ km} \). Recall that in the flight experiment RAMC-II [11–13] for the diagnosis of the degree of ionization of air in the compressed layer microwave sensors with a frequency \( f_L \sim 1 \text{ GHz} \) and \( f_X \sim 10 \text{ GHz} \) were used. With the use of these sensors, electron concentrations of \( n_e \sim 10^{10} \text{ cm}^{-3} \) were detected. Note that the critical electron concentration required to reflect the radio signal can be predicted from formula

\[
n_{e,cr} = 1.24 \times 10^4 f_{mic}^2 \approx 1.24 \times 10^9 f_{GHz}^2 , \ \text{cm}^{-3}
\]

In the case considered in figure 2, \( c \), the electron concentration in the compressed layer above the surface of the wedge reaches \( n_e \sim 10^{11} \text{ cm}^{-3} \). In this case, the distribution of electron and \( \text{NO}^+ \) ion concentrations along the thickness of the compressed layer is shown in figure 4, \( a \), from which it is clearly seen that the thickness of the ionized region reaches almost 10 cm, and the degree of ionization falls insignificantly along the wedge generatrix.

The distributions of the translational and vibrational temperatures \( \text{N}_2 \) over the height of the compressed layer in these same sections (figure 4, \( b \)) show a good thermalization of the internal degrees of freedom. The distribution of the concentrations of atomic nitrogen (the result of \( \text{N}_2 \) dissociation) and \( \text{NO} \) molecules (formed as a result of the chain of chemical transformations) in figure 3, \( a \), as well as the concentrations of \( \text{O} \) atoms and \( \text{O}_2 \) molecules in figure 3, \( b \), give an idea of the degree of dissociation of air molecules and the configuration of the field of \( \text{NO} \) molecules, which serve as the primary source of electrons.

Figures 5–7 show the results of calculations of aerophysics over a blunted wedge moving at a height of \( H = 20 \text{ km/s} \) at a speed of \( V_\infty = 3 \text{ km} \), that is, at a reduced speed of 1 km/s compared to the previous variant. The expected drop in translational and vibrational temperatures in the compressed layer is observed (figure 5, \( a \)). We note a noticeable decrease in the concentration of electrons in the compressed layer (figure 5, \( c \)) and \( \text{NO}^+ \) ions. From the distributions of ion concentrations over the thickness of the compressed layer in different sections along \( x \) (figure 7, \( a \)), it is evident that the largest electron concentration does not exceed \( n_e \sim 10^{11} \text{ cm}^{-3} \). This means that with a further decrease in the velocity of the blunted wedge, the electron concentrations will not reach their critical value.
Figure 2. The fields of the translational temperature $T(a, \text{above})$ and the vibrational temperature $T_v(a, \text{from below})$, the longitudinal velocity $V_x = u/V_w$ ($b, \text{from above}$) and the Mach number ($b, \text{from below}$), the electron concentration ($c, \text{from above}$) and NO$^+$ ions ($c, \text{from below}$). The temperature is in K, the concentration is in cm$^{-3}$; $H = 20$ km, $V_w = 4$ km/s.

When the altitude of the flight is increased up to $H = 30$ km, the nonequilibrium effects are more clearly manifested. Figures 8–10 and 11–13 show the results of calculations for aerophysics of a blunted wedge with a smaller half angle, $\phi = 3^\circ$. At $V_w = 4$ km/s a faster decrease in the translational and vibrational temperatures along the wedge generates, but the concentration of electrons and NO$^+$ ions near the blunting is higher, $n_e \sim 10^{12}$ cm$^{-3}$. With a decrease in velocity to $V_w = 3$ km/s (figures 11–13), the temperature and concentration fall faster than at $H = 20$ km. The maximum electron concentration in the compressed layer decreases up to $n_e \sim 10^{10}$ cm$^{-3}$ at half length of the wedge. At this altitude, there is a noticeable difference between translational and vibrational temperatures along the entire lateral surface (figures 10 and 13).
Figure 3. Fields of concentrations of N (a, above) and N$_2$ (a, below) molecules, atoms O (b, above) and molecules O$_2$ (b, below). Concentrations in cm$^{-3}$; $H = 20$ km, $V_\infty = 4$ km/s.

Figure 4. Axial distributions of the electron concentration (left), as well as translational and vibrational temperatures N$_2$ in 5 sections along the x axis ($x_1 = 4.92$ cm, $x_{15} = 19.5$ cm, $x_{29} = 34.2$ cm, $x_{42} = 49$ cm, $x_{55} = 64$ cm). $H = 20$ km, $V_\infty = 4$ km/s.
Figure 5. The fields of the translational temperature $T$ (a, above) and the vibrational temperature $T_v$ of $N_2$ (a, from below), the longitudinal velocity $V_x = u/V_\infty$ (b, from above) and the Mach number (b, from below), the electron concentration (c, from above) and NO$^+$ ions (c, from below). The temperature is in K, the concentration is in cm$^{-3}$; $H = 20$ km, $V_\infty = 3$ km/s.
Figure 6. Fields of concentrations of $N$ ($a$, above) and $N_2$ ($a$, below) molecules, atoms $O$ ($b$, above) and molecules $O_2$ ($b$, below). Concentrations in cm$^{-3}$; $H = 20$ km, $V_\infty = 3$ km/s.

Figure 7. Axial distributions of the electron concentration (left), as well as translational and vibrational temperatures $N_2$ in 5 sections along the $x$ axis. $H = 20$ km, $V_\infty = 3$ km/s.
Figure 8. The fields of the translational temperature $T$ (a, above) and the vibrational temperature $T_v$ of $N_2$ (a, from below), the longitudinal velocity $V_x = u/V_\infty$ (b, from above) and the Mach number (b, from below), the electron concentration (c, from above) and NO$^+$ ions (c, from below). The temperature is in K, the concentration is in cm$^{-3}$; $H = 30$ km, $V_\infty = 4$ km/s.
Figure 9. Fields of concentrations of N (a, above) and N\textsubscript{2} (a, below) molecules, atoms O (b, above) and molecules O\textsubscript{2} (b, below). Concentrations in cm\textsuperscript{-3}; H = 30 km, V\textsubscript{c} = 4 km/s.

Figure 10. Axial distributions of the electron concentration (left), as well as translational and vibrational temperatures N\textsubscript{2} in 5 sections along the x axis. H = 30 km, V\textsubscript{c} = 4 km/s.
Figure 11. The fields of the translational temperature $T$ (a, above) and the vibrational temperature $T_v$ of $N_2$ (a, from below), the longitudinal velocity $V_x = u/V_\infty$ (b, from above) and the Mach number (b, from below), the electron concentration (c, from above) and NO$^+$ ions (c, from below). The temperature is in K, the concentration is in cm$^{-3}$; $H = 30$ km, $V_\infty = 3$ km/s.
Figure 12. Fields of concentrations of N (a, above) and N\textsubscript{2} (a, below) molecules, atoms O (b, above) and molecules O\textsubscript{2} (b, below). Concentrations in cm\textsuperscript{-3}; H = 30 km, V\textsubscript{∞} = 3 km/s.

Figure 13. Axial distributions of the electron concentration (left), as well as translational and vibrational temperatures N\textsubscript{2} in 5 sections along the x axis. H = 30 km, V\textsubscript{∞} = 3 km/s.
The next series of drawings show the flow field above blunt wedges at still higher altitudes. At heights of \( H = 40 \text{ km}, 50 \text{ km} \) and \( 60 \text{ km} \) with a successive decrease in speed \( V_\infty = 5 \text{ km/s}, 4 \text{ km/s} \) and \( 3 \text{ km/s} \) (see figures 14–16, 17–19 and 20–22; figures 23–25, 26–28 and 29–31; figures 32–34, 35–37 and 38–40) there is a sharp decrease in concentrations \( n_e \) in the compressed layer. The flow becomes more non-equilibrium.

**Figure 14.** The fields of the translational temperature \( T \) (\( a \), above) and the vibrational temperature \( T_v \) of \( N_2 \) (\( a \), from below), the longitudinal velocity \( V_x = u/V_\infty \) (\( b \), from above) and the Mach number (\( b \), from below), the electron concentration (\( c \), from above) and \( \text{NO}^+ \) ions (\( c \), from below). The temperature is in K, the concentration is in cm\(^{-3}\), \( H = 40 \text{ km}, V_\infty = 5 \text{ km/s} \).
Figure 15. Fields of concentrations of \( N \) (\( a \), above) and \( N_2 \) (\( a \), below) molecules, atoms \( O \) (\( b \), above) and molecules \( O_2 \) (\( b \), below). Concentrations in \( \text{cm}^{-3} \); \( H = 40 \text{ km} \), \( V_e = 5 \text{ km/s} \).

Figure 16. Axial distributions of the electron concentration (left), as well as translational and vibrational temperatures \( N_2 \) in 5 sections along the \( x \) axis. \( H = 40 \text{ km} \), \( V_e = 5 \text{ km/s} \).
Figure 17. The fields of the translational temperature $T$ (a, above) and the vibrational temperature $T_v$ of N$_2$ (a, from below), the longitudinal velocity $V_x = u / V_e$ (b, from above) and the Mach number (b, from below), the electron concentration (c, from above) and NO$^+$ ions (c, from below). The temperature is in K, the concentration is in cm$^{-3}$; $H = 40$ km, $V_e = 4$ km/s.
Figure 18. Fields of concentrations of $N$ (a, above) and $N_2$ (a, below) molecules, atoms $O$ (b, above) and molecules $O_2$ (b, below). Concentrations in cm$^{-3}$; $H = 40$ km, $V_\infty = 4$ km/s.

Figure 19. Axial distributions of the electron concentration (left), as well as translational and vibrational temperatures $N_2$ in 5 sections along the $x$ axis. $H = 40$ km, $V_\infty = 4$ km/s.
Figure 20. The fields of the translational temperature $T$ (a, above) and the vibrational temperature $T_v$ of $N_2$ (a, from below), the longitudinal velocity $V_x = u/V_e$ (b, from above) and the Mach number (b, from below), the electron concentration (c, from above) and NO$^+$ ions (c, from below). The temperature is in K, the concentration is in cm$^{-3}$; $H = 40$ km, $V_e = 3$ km/s.
Figure 21. Fields of concentrations of N (a, above) and N₂ (a, below) molecules, atoms O (b, above) and molecules O₂ (b, below). Concentrations in cm⁻³; \( H = 40 \) km, \( V_\infty = 3 \) km/s.

Figure 22. Axial distributions of the electron concentration (left), as well as translational and vibrational temperatures N₂ in 5 sections along the \( x \) axis. \( H = 40 \) km, \( V_\infty = 3 \) km/s.
Figure 23. The fields of the translational temperature $T$ (a, above) and the vibrational temperature $T_v$ of $N_2$ (a, from below), the longitudinal velocity $V_x = u/V_\infty$ (b, from above) and the Mach number (b, from below), the electron concentration (c, from above) and NO$^+$ ions (c, from below). The temperature is in K, the concentration is in cm$^{-3}$; $H = 50$ km, $V_\infty = 5$ km/s.
Figure 24. Fields of concentrations of $N$ (a, above) and $N_2$ (a, below) molecules, atoms $O$ (b, above) and molecules $O_2$ (b, below). Concentrations in cm$^{-3}$; $H = 50$ km, $V_\infty = 5$ km/s.

Figure 25. Axial distributions of the electron concentration (left), as well as translational and vibrational temperatures $N_2$ in 5 sections along the $x$ axis. $H = 50$ km, $V_\infty = 5$ km/s.
Figure 26. The fields of the translational temperature $T$ ($a$, above) and the vibrational temperature $T_v$ of $N_2$ ($a$, from below), the longitudinal velocity $V_x = u/V_\infty$ ($b$, from above) and the Mach number ($b$, from below), the electron concentration ($c$, from above) and $NO^+$ ions ($c$, from below). The temperature is in K, the concentration is in cm$^{-3}$; $H = 50$ km, $V_\infty = 4$ km/s.
Figure 27. Fields of concentrations of $N$ (a, above) and $N_2$ (a, below) molecules, atoms $O$ (b, above) and molecules $O_2$ (b, below). Concentrations in cm$^{-3}$; $H = 50$ km, $V_\infty = 4$ km/s.

Figure 28. Axial distributions of the electron concentration (left), as well as translational and vibrational temperatures $N_2$ in 5 sections along the $x$ axis. $H = 50$ km, $V_\infty = 4$ km/s.
Figure 29. The fields of the translational temperature $T$ (a, above) and the vibrational temperature $T_v$ of N$_2$ (a, from below), the longitudinal velocity $V_x = u/V_0$ (b, from above) and the Mach number (b, from below), the electron concentration (c, from above) and NO$^+$ ions (c, from below). The temperature is in K, the concentration is in cm$^{-3}$; $H = 50$ km, $V_0 = 3$ km/s.
Figure 30. Fields of concentrations of $N$ (a, above) and $N_2$ (a, below) molecules, atoms $O$ (b, above) and molecules $O_2$ (b, below). Concentrations in cm$^{-3}$; $H = 50$ km, $V_e = 3$ km/s.

Figure 31. Axial distributions of the electron concentration (left), as well as translational and vibrational temperatures $N_2$ in 5 sections along the $x$ axis. $H = 50$ km, $V_e = 3$ km/s.
Figure 32. The fields of the translational temperature $T$ (a, above) and the vibrational temperature $T_v$ of N$_2$ (a, from below), the longitudinal velocity $V_x = u/V_\infty$ (b, from above) and the Mach number (b, from below), the electron concentration (c, from above) and NO$^+$ ions (c, from below). The temperature is in K, the concentration is in cm$^{-3}$; $H = 60$ km, $V_\infty = 5$ km/s.
Figure 33. Fields of concentrations of $N$ (a, above) and $N_2$ (a, below) molecules, atoms $O$ (b, above) and molecules $O_2$ (b, below). Concentrations in cm$^{-3}$; $H = 60$ km, $V_o = 5$ km/s.

Figure 34. Axial distributions of the electron concentration (left), as well as translational and vibrational temperatures $N_2$ in 5 sections along the $x$ axis. $H = 60$ km, $V_o = 5$ km/s.
Figure 35. The fields of the translational temperature $T$ ($a$, above) and the vibrational temperature $T_v$ of $\text{N}_2$ ($a$, from below), the longitudinal velocity $V_x = u/V_\infty$ ($b$, from above) and the Mach number ($b$, from below), the electron concentration ($c$, from above) and NO$^+$ ions ($c$, from below). The temperature is in K, the concentration is in cm$^{-3}$; $H = 60$ km, $V_\infty = 4$ km/s.
Figure 36. Fields of concentrations of N (a, above) and N\textsubscript{2} (a, below) molecules, atoms O (b, above) and molecules O\textsubscript{2} (b, below). Concentrations in cm\textsuperscript{-3}; \(H = 60\) km, \(V_\infty = 4\) km/s.

Figure 37. Axial distributions of the electron concentration (left), as well as translational and vibrational temperatures N\textsubscript{2} in 5 sections along the \(x\) axis. \(H = 60\) km, \(V_\infty = 4\) km/s.
Figure 38. The fields of the translational temperature $T$ (a, above) and the vibrational temperature $T_v$ of N$_2$ (a, from below), the longitudinal velocity $V_x = u/V_\infty$ (b, from above) and the Mach number (b, from below), the electron concentration (c, from above) and NO$^+$ ions (c, from below). The temperature is in K, the concentration is in cm$^{-3}$, $H = 60$ km, $V_\infty = 3$ km/s.
Figure 39. Fields of concentrations of $N$ (a, above) and $N_2$ (a, below) molecules, atoms $O$ (b, above) and molecules $O_2$ (b, below). Concentrations in cm$^{-3}$; $H = 60$ km, $V_e = 3$ km/s.

Figure 40. Axial distributions of the electron concentration (left), as well as translational and vibrational temperatures $N_2$ in 5 sections along the $x$ axis. $H = 60$ km, $V_e = 3$ km/s.
Figure 41. Distribution of electron concentrations along the surface of blunted wedges for all heights and velocities (a) and for relatively high velocities (b).

If at relatively high velocities the vibrational temperature $T_v$ of N₂ molecules in the compressed layer at the lateral surface exceeds the translational temperature $T$, then at low velocities the reverse situation is observed: $T_v < T$. This is explained by the fact that at relatively low speeds at high
altitudes the vibrational temperature \( T_v \) does not have time to reach the translational temperature \( T \) even near to blunted nose.

The distribution of the maximum electron concentrations along the generatrix of a blunt wedge in a wide range of heights and velocities is shown in figure 41. If the critical level of the electron density is \( n_e^* \approx 10^{10} \text{ cm}^{-3} \), then at an altitude \( H > 30 \text{ km} \) and a velocity \( V_{\infty} < 3 \text{ km/s} \), the ionization level is low. However, as mentioned above, the critical concentration depends not only on the parameters of the ionized air, but also on the frequency of the probing electromagnetic wave.

As the resume, it can be stated that the presented results of a preliminary analysis of aerophysics over a blunted wedge over a wide range of heights and velocities make it possible to determine a program for further studies of the nonequilibrium effects accompanying gas motion at moderate hypersonic speeds.

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