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FOREIGN TECHNOLOGY DIVISION

EXPERIMENTAL INVESTIGATION OF SPECTRAL PROPERTIES OF AIR AT HIGH TEMPERATURES

by

A. A. Kon'kov, A. P. Ryazin and V. S. Rudnev

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By: A. A. [illegible], A. P. Ryazin and V. S. Rudnev

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ABSTRACT

(U)Experimental investigations were made of spectral absorption indexes of air at temperatures above 10,000 degrees K with the aim of determining more accurately the role of the thermal radiation at very high Mach numbers. The shock tube used in the experiment was described earlier by Ambartsumyan, Ryasin and Kon'kov (Fizicheskaya gazodinamika ionizirovannykh i khimicheski reagiruyushchikh gazov. Moscow, Izd-vo Nauka). It could produce shock-wave velocities from 2 to 10 km/sec. A block diagram of the experimental setup is shown and its operation is described in some detail. The methods and results of earlier Soviet and foreign investigations are evaluated with the view to identifying the causes of discrepancies between the theories and experimental data which exist, to a systematically increasing degree, at shock wave velocities above Mach 24. In the experiments, the air temperature heated by the reflected shock wave was determined by simultaneous and independent measurement of the radiative and absorptive capabilities of air at a given wavelength. By comparing the data thus obtained to those derived by calculations, certain corrections are proposed in earlier work by Plastinin and Baula (Issledovaniya po fizicheskoy gazodinamike. Sbornik. Moskva, Izd-vo Nauka, 1965) and Biberman and Plastinin (Teplofizika vysokikh temperatur, v. 4, no. 2, 1966). The authors thank A. A. Volkov for help. Orig. art. has: 12 figures.

U. S. BOARD ON GEOGRAPHIC NAMES TRANSLITERATION SYSTEM

Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
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Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

* ye initially, after vowels, and after ъ, ь; e elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

EXPERIMENTAL INVESTIGATION OF SPECTRAL PROPERTIES OF AIR AT HIGH TEMPERATURES

A. A. Kon'kov, A. P. Ryazin and V. S. Rudnev

Published results of calculations [1-4] of spectral indices of absorption of air and absorption cross sections of its components essentially differ from each other. Calculations are based on experimentally measured values of squares of matrix elements of dipole moments of electron transitions of molecules, but these values are not always measured sufficiently reliably. There are also differences in the methods of calculation. Experimental determination of radiant thermal flux [5] in the critical point of a model, under conditions corresponding to a height of flight of 37 km and Mach number 28, showed that radiant heat flux plays a predominant role. A comparison of the value of experimentally measured heat flux with that calculated in an assumption of thermodynamic equilibrium showed that the computed value is twice as large as the experimental. Value of radiant heat flux is determined by the values of spectral indices of absorption. Experimental determination of spectral indices of absorption of air at temperatures higher than 10,000°K still is lacking, in connection with which this work was undertaken.

1. Construction of Experimental Unit

A detailed description of the shock tube used in the present experiments is given in [6]. Its basic design parameters are as follows: length of low pressure section 400 cm; length of high pressure section 170 cm; internal diameter 3 cm. The high pressure section was filled either with hydrogen (to a pressure of 150 atm) or a mixture of 10% oxygen, 20% hydrogen, and 70% helium (to a pressure of 40 atm).

Velocity range of the shock wave which could be realized in this unit was 2-10 km/s. Velocity of shock wave was measured by a system of pickups. Ionization and photosensitive devices were used. The ionization pickup constitutes two electrodes, the distance between which is around 2 mm, and to which is applied a voltage of around 100 V. At the time of arrival of the shock wave in the circuit of the pickup current appeared, and on the load impedance a voltage pulse, which was then recorded by an oscillograph. As photosensitive devices we used [FEU-29] (ФЭУ-29) photomultipliers. Recording of signals was done on an [IO-4] (ИО-4) oscillograph. Parameters of the gas, heated by the reflected shock wave, were calculated based on the incident shock wave. Accuracy of such a calculation was confirmed by direct measurements of temperature, the results of which are given below.

2. Spectral Composition of Radiation and Dependence of Index of Absorption of Air on Length of Wave

For investigation of spectral characteristics of air we used the method of simultaneous recording of expanded spectrograms and absolute intensity of radiation for a certain section of the spectrum.

The method for recording of expanded spectrograms is described in work [6]. Briefly it consists of the following. A slanted slot, moving in a direction perpendicular to the slot of the spectrograph, at different moments of time opens different sections of the entrance slit, thereby recording the expanded spectrum of radiation of a gas on photographic film. A device operating on the basis of this principle made it possible to obtain expanded spectrograms with a resolution of 5-10 μs and a total time of action of 40-200 μs.

Measurement of absolute intensity of radiation was conducted with the help of a system of a monochromator and a photomultiplier, which was calibrated on a [SI-8-200] (СИ-8-200) ribbon tungsten lamp.

General circuit of the experimental unit is shown in Fig. 1. A shock wave, in going past the ionization pickup, initiated a pulse which actuated synchronization block 6. From the synchronization block in specific moments of time the pulses proceeded to power pack 7 of the spectrum scanning shutter 9. Also actuated were the scans of the oscillographs for measuring intensity of radiation of air and velocity of the shock wave. Spectrograms were recorded with the help of an [ISP-28] (ИСП-28) spectrograph 8 on panchrome-X film with a sensitivity of 1000 GOST units. The photoelectrical channel of the unit consisted of the following elements: lens 12, depicting a representation of radiating volume of gas on the entrance slit, neutral light filters 13, making is possible in wide limits to change the sensitivity of the system, a [ZMR-3] (ЗМР-3) monochromator 1, FEU-29 photomultiplier 2, power pack 3 for the photomultiplier, and an IO-4 oscillograph. The monochromator was arranged so that its optical axis coincided with the optical axis of the spectrograph and was perpendicular to the axis of the shock tube. On the entrance slit of the monochromator was depicted a representation of the layer of gas, located five mm from the end of the shock tube, therefore at distance of 5 mm from the end on the external surface of the viewing window a slot with a width of around 1 mm was installed.

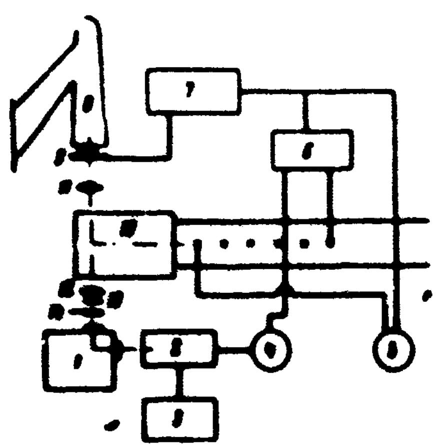

Fig. 1. Arrangement of experimental unit for investigation of spectral characteristics of gases.

Figure 2 shows the expanded spectrum of radiation of air, heated by a reflected shock wave. Identified in the spectrum are the bands of the first negative system of nitrogen, and also lines of impurities – iron, chromium, calcium, and others. Identification of lines of impurities was conducted in several stages. Preliminarily with the help of reference lines of iron wavelengths were deciphered and determined for all the lines encountered in the spectra of air. Lines of impurities in spectra of radiation of air were greatly widened and therefore it was difficult to determine exactly the length of their wave. Therefore spectra of radiation were obtained [7] for krypton and xenon at 20,000-25,000°K, where the lines of impurities in the spectrum appear only in absorption. The reversed lines were sufficiently narrow and the accuracy of determination of their wavelength was considerably higher than accuracy of determination based on spectra of radiation. If the mutual location of lines in the spectra of air, krypton, and xenon was identical, and wavelength coincided with the wavelength of the line of impurity, then it was considered established that the given line belongs to the impurity.

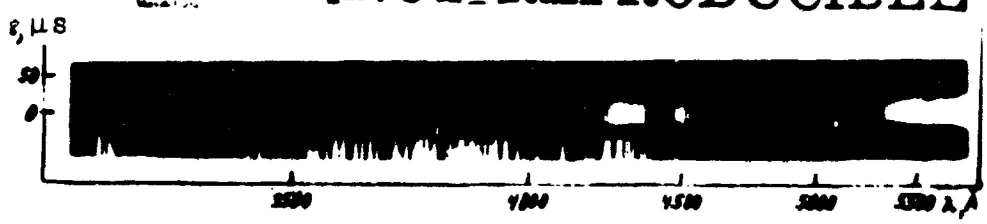

Fig. 2. Expanded spectrum of radiation of air at a temperature of 11,500°K and pressure of 60 atm.

Spectrograms were processed with the help of the method of heterochromatic photometry [6]. A graph variant of this method was used; on the same photographic plate with the help of an [MF-4] (МФ-4) microphotometer microphotograms were recorded of the spectra of an SI-8-200 ribbon tungsten lamp. These were obtained with the help of a nine-step reducer on the same film as the investigated spectrum. Inasmuch as dependence of the radiative capacity of tungsten on wavelength has been studied quite sufficiently, then these microphotograms make it possible to convert from blackenings in the spectrum of the investigated gas to the dependence of intensity in relative units on wavelength.

This variant of the method makes it possible to eliminate the bulky and laborious construction of characteristic curves of film for every wavelength. As was shown above, the resulting relative dependence of intensity on wavelength was standardized to absolute values with the help of data obtained on a photoelectric channel. For standardization we selected a section of the spectrum in the region of wavelengths of 4850 Å with a width of around 10 Å. This sector of the spectrum was selected because it is free from lines of impurities, as can be seen from the spectrogram (see Fig. 2). As a result the dependence of radiative capacity on wavelength was obtained. Then with the help of the laws of Kirchhoff and Beer the dependence of index of absorption on wavelength was determined.

Such a method of determination of spectral indices of absorption assumes a known temperature of the gas. To consider the temperature of air under conditions of the given experiment as equal to that calculated on the basis of laws of conservation is not sufficiently founded, therefore the accuracy of such a calculation was confirmed by direct measurements of the temperature of the gas, the results of which are expounded below.

Figure 3 (curve 1) gives the experimental dependence of index absorption of air on wavelength for a temperature of 11,500°K and pressure of 60 atm. Here are cited all the values of index of absorption of air, obtained by means of direct measurement of blackenings on the spectrogram. Vertical lines show the values of indices of absorption, measured in those points of the spectrum where the lines of impurities lie. Height of lines corresponds to the value of index of absorption, measured directly at that point of the spectrum. From a consideration of the given curve, and also the spectrogram (see Fig. 2), it follows that the sections free from lines of impurities are very few.

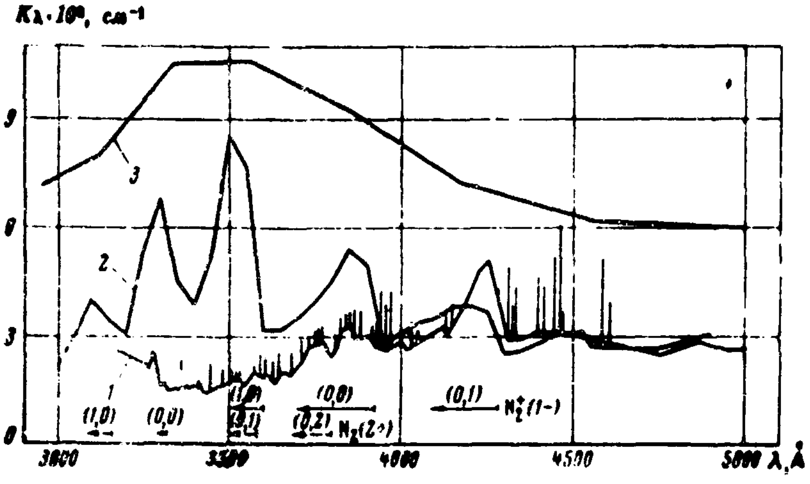

Fig. 3. Dependence of index of absorption of air on wavelength. 1 – experimental data from this work, temperature 11,500°K, pressure 60 atm; 2 – calculation data according to [2, 3], temperature 12,000°K, pressure 50 atm; 3 – calculation data according to [4], temperature 12,000°K, pressure 50 atm.

Let us note that the method (very widespread in the literature) of investigation of radiative capacity of gases by means of measurement of radiation in separate sectors of the spectrum without simultaneous recording of spectrograms contains very much uncertainty, inasmuch as, in radiative capacity measured in su a way a contribution an be made by lines of impurities, which are present as one can see from Figs. 2 and 3, in a sufficiently large quantity.

Figure 4 (curve 1) shows the experimentally measured dependence of index of absorption on wavelength for air at 10,500°K and pressure of 50 atm. Here lines of impurities are excluded from consideration and values are given for index of absorption relative only to air.

Accuracy of measurement of spectral indices of absorption is determined by accuracy of the method of heterochromatic photometry and accuracy of measurement of the standardizing factor. Accuracy of the method of heterochromatic photometry is made up of accuracy of calibration of a standard source and accuracy of measurement of blackenings with the help of a microphotometer and comprises ±20%. Accuracy of measurement of standardizing factor is made up of accuracy

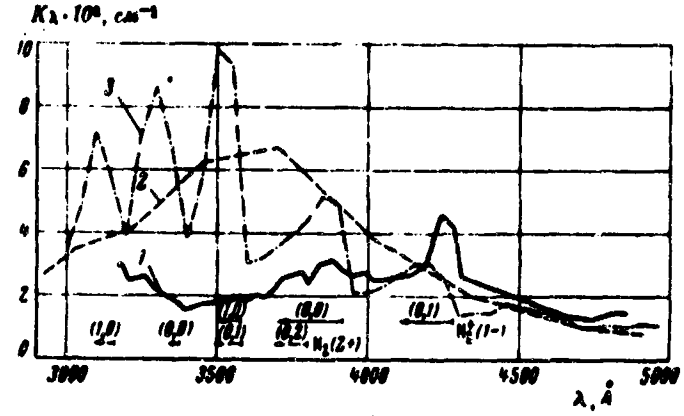

Fig. 4. Dependence of index of absorption of air on wavelength. 1 – experimental data from this work, temperature 10,500°K, (pressure 50 atm); 2 – calculation data according to [2, 3], temperature 10,000°K; 3 – calculation data according to [4], temperature 10,000°K.

of setting up of standard source, its calibration, measurement of potential with the help of an oscillograph, and determination of parameters of the gas and comprises ±25%.

3. Measurement of Temperature of Air Which Has Been Heated by a Reflected Shock Wave

Temperature of air, heated by a reflected shock wave, was measured with the help of the Kirchhoff law. Method of determination of temperature consisted of the simultaneous and independent measurement of radiative and absorbing capacities of the air for a specific wavelength. Their ratio, according to the Kirchhoff law, is a Planck function, depending, at a given fixed wavelength, only on temperature of the radiating object.

The general arrangement for location of instruments is given in Fig. 5. The system consists of two channels: on the first was recorded the absorbing capacity of the gas, on the second – radiative capacity. With this goal the entrance and exit slits of the monochromator were divided into two parts and accordingly beyond the exit slit two recording channels were set up. The first channel worked in the following manner. A representation of sounding pulse light 11 was projected by lenses 12-14 approximately on the axis of the shock tube, and then by lens 15 on the upper part of the entrance slit on the ZMR-3 monochromator 1. Radiation, passing the monochromator and being reflected from a turning mirror, was received by a FEU-29 photomultiplier 4 and was recorded by an IO-4 oscillograph 7. Radiation from the investigated object arrived at the lower part of the slit of monochromator 1 and then was recorded by a second channel, consisting of a FEU-29 photomultiplier 3 and IO-4 oscillograph 7. The photomultipliers were supplied with power by a [VS-16] (BC-16) type block 5. Synchronization of the work of both channels and pulse light source was carried out by electronic block 8. Calibration of the system in absolute units was conducted with the help of an SI-8-200 ribbon tungsten lamp, which was set up at the point of intersection of the axes of the shock tube and optical system, whereas other parameters of optical system remained the same as during the experiment.

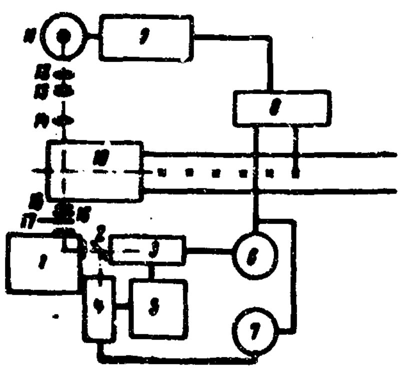

Fig. 5. Arrangement for location of instruments for measurement of air temperature.

An auxiliary pulse source worked on the circuit shown in Fig. 6. Its principle of operation was that a long line, consisting of five LC cells, was discharged through a textolite capillary with a hole diameter of 2-3 mm. Sequence of operation of elements of the pulse source consisted of the following. The pulse from the synchronization block reached the grid of thyratron Л. The thyratron was opened and through it capacitor C_1 was discnarged. As a result, on the secondary winding of transformer Tp_1 a voltage pulse was formed which initiated the breakdown of discharger P_1, and in the circuit consisting of capacitor C_2 and primary winding of transformer Tp_2 high-frequency oscillations developed. Then voltage was increased on the secondary winding of transformer Tp_2. The gas of discharger P_2 is selected in such a way that its breakdown set in at a voltage of around 20 kV. After breakdown the high-frequency oscillations appearing in circuit C_3L_1 initiate the breakdown of discharge gas of capillary P_3. The long line, consisting of five LC cells charged up to a voltage of 3 kV, was discharged through the capillary.

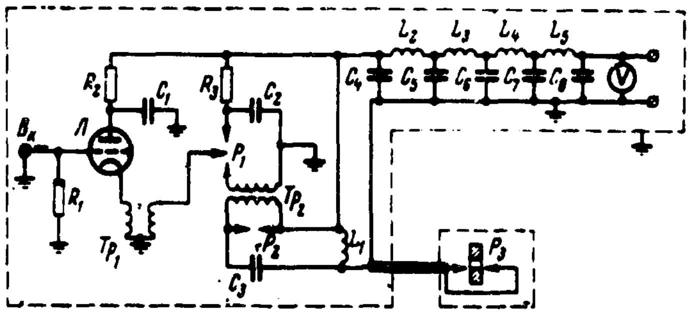

Fig. 6. Electrical circuit of the pulse light source.

Spectrum of radiation of the pulse source (Fig. 7) was continuous with a small number of reversed lines. Brightness and color temperature of it within limits of errors coincide and comprise 30,000°K.

It follows from this that the source radiates like a blackbody with a temperature of 30,000°K. The pulse of radiation of the source has a trapezoidal form and pulse width of radiation is around 300 μs, where the time, during which radiation remains constant is around 200 μs.

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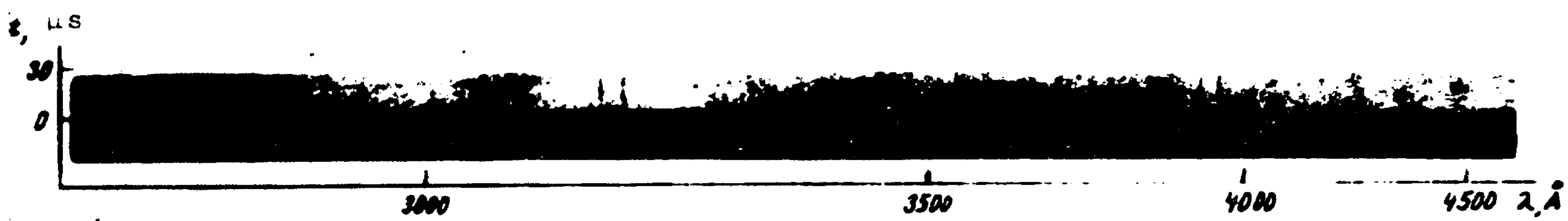

Fig. 7. Expanded spectrum of radiation of pulse light source.

The experiment was conducted in the following way. After arrival of the shock wave at the ionization pickup the latter actuated the synchronization block, which in its turn initiated the beginning of operation of the power pack of the pulse light source and the sweeps of the oscillographs. Intervals of time were selected in such a manner that the moment of arrival of reflected shock wave coincided with the sector of constancy of radiation of the capillary source. The first channel recorded the value $[I_{\lambda_0}(1 - A_\lambda) + cI_\lambda]$, and the second — value I_λ. Here I_{λ_0} — intensity of radiation of capillary source; A_λ — absorbing ability of investigated gas; I_λ — emissive power of gas; c — ratio of sensitivities of channels.

Since $c \ll 1$, then in first approximation one may assume that from data, obtained on the first channel, follows directly the value of absorbing ability, whereas based on data of the second it is possible to calculate emissive power. Inasmuch as the ratio of sensitivities of channels was measured, then in the event of necessity it is possible to introduce the corresponding correction in the data obtained on the first channel.

Temperature of the air was measured in a section, located at a distance of 4 mm from the end of the shock tube. For measurement of temperature a sector of spectrum was selected with a width of 5 Å near 4238 Å. As can be seen from the spectrogram (see Fig. 2) and the dependence of index of absorption on wavelength (see Fig. 3), the given sector of the spectrum is free from lines of impurities and corresponds to maximum of absorption (0.1) of the band of the first negative system of nitrogen.

Figure 8 shows the dependence of intensity of radiation (a) and absorbing ability (b) on time. As can be seen from the graphs, radiation after arrival of reflected shock wave remains constant for 10-30 μs (sometimes even considerably more), then decreases quite rapidly to a relatively small value, and remains on this level for a sufficiently long time. After arrival of the reflected shock wave absorption holds constant (10-30 μs) and then increases to a unit.

The same effect of "shielding" of radiation of the auxiliary source by the investigated gas after encounter of the reflected shock wave with the contact region was observed earlier in work [6]. A reliable interpretation of this effect is lacking.

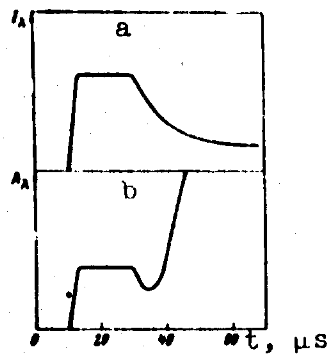

Fig. 8.

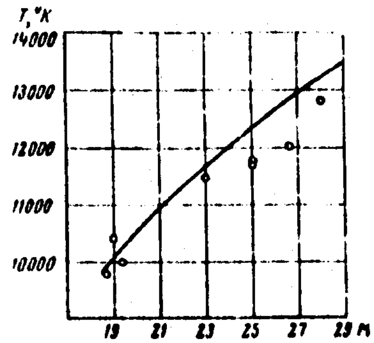

Fig. 9.

Fig. 8. Dependence of intensity of radiation (a) and absorbing capacity (b) on time.

Fig. 9. Dependence of temperature of air, heated by a reflected shock wave, on Mach number of incident shock wave.

In Fig. 9 the experimental values of temperature of air are shown by the small circles. The initial pressure of air in the sector of low pressure is 5 mm Hg. Accuracy of measurement of temperature comprised ±1000°. The continuous curve shows the dependence of temperature of air, heated by the reflected shock wave, on Mach number of incident shock wave. These data are taken from work [8], where temperature was calculated on the basis of laws of conservation. Computed values of temperature in work [8] are given only up to Mach numbers of 24. Data for larger Mach numbers are obtained by means of extrapolation of these data.

Calculation and experimental temperature of air (see Fig. 9), heated by reflected shock wave up to Mach numbers 23, coincide. For larger Mach numbers a systematic divergence is observed. however, if one were to consider accuracy of measurement of temperature and the circumstance that calculation data in this region are extrapolated, then it is impossible to ascertain confidently divergence of experimental and calculation data.

4. Discussion of Results

Data in work [1] should be considered obsolete and subsequently they are not being considered.

From a consideration of the graphs shown in Fig. 3, it follows that the values of index of absorption, obtained on the basis of work [4], lie higher than experimental values in the entire investigated region of the spectrum. The latter is connected with absorption of the cross section accepted in [4], for the negative ion of nitrogen, which is taken from work [9], is assumed not dependent on wavelength and equal to $4 \cdot 10^{-17}$ cm^2. At 10,000°K radiation of negative ion of nitrogen was not considered, therefore in the region of 4000 to 5000 Å coincidence of experimental and computed values is satisfactory. Data from works [2, 3] in the region of 4000-5000 Å describe the experimental data quite well. In the region of wavelengths of 3000 to 4000 Å there is a divergence of experimental and computed values. Let us note that in works [2, 4] oscillator strength of the second positive system of nitrogen is accepted as close to a value of 0.057, obtained in work [10]. However, in this work there is no analysis of the possible influence of impurities, the radiation of which, as was noted above, can make an additional contribution. This compels one to consider this value of oscillator strength of the second positive system of nitrogen as the upper limit. The closest to true, as this follows from recent works, should apparently be considered the value 0.039 obtained in work [11], where the lifetime of excited state of second positive system of nitrogen was measured. Oscillator strength of the first negative system of nitrogen in work [4] is accepted as equal to 0.035, in conformity with data from work [11]. It is assumed that adiabatic approximation is accurate. The authors of work [2] originated from the same value of oscillator strength of the first negative system of nitrogen, but here it is accepted that the square of the matrix element of dipole moment of transition Re^2 depends on internuclear distance. The dependence accepted in [2], of Re^2 on internuclear distance is shown by the dotted line in Fig. 10.

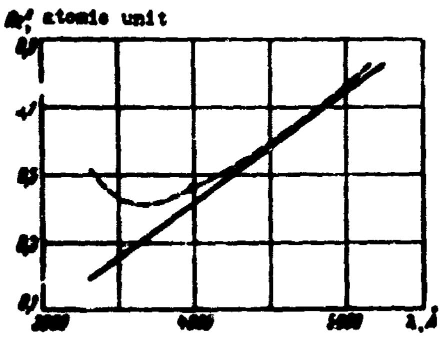

Fig. 10. Dependence of square of matrix element of dipole moment of electron transition of the first negative system of nitrogen on wavelength.

It follows from what was said above that the closest to true value of oscillator strength of the first negative system of nitrogen should be considered 0.032-0.035, for the second positive – 0.039. Inasmuch as in the spectrum of air, obtained in this work, no increase of radiation was observed in the region of 3500 Å, then as the dependence of square of matrix element of first negative system of nitrogen on wavelength we accepted the dependence shown in Fig. 10 by the unbroken line.

Proceeding from what was expounded, it was expedient to introduce the following changes in the calculation data of works [2] and [4]:

1) from the data of work [4] exclude the contribution of negative ion of nitrogen;

2) for the second positive system of nitrogen take the value of oscillator strength 0.039;

3) dependence of square of matrix element accepted in the form shown in Fig. 10 by the unbroken curve.

These changes were introduced in the calculations of works [2] and [4]. The dependences of index of absorption on wavelength, obtained after introduction of these changes, were compared with experimental data. The results of the comparison are shown in Figs. 11 and 12. From the graphs it follows that as a result of changes made satisfactory agreement is observed between experimental and calculation data, with the exception of the region of 3500 Å.

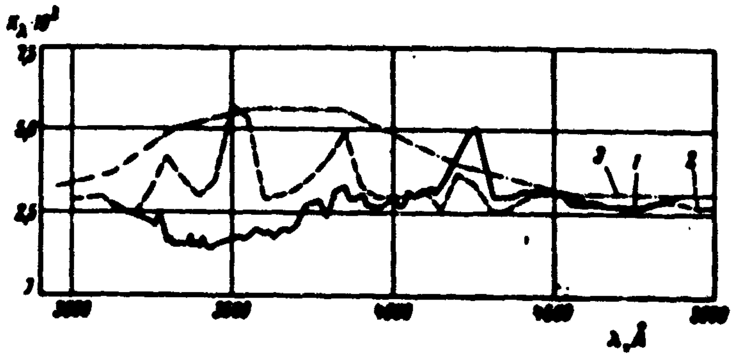

Fig. 11. Dependence of index of absorption of air on wavelength. 1 — experimental data of this work, temperature 11,500°K, pressure 60 atm; 2 — according to data of works [2, 3] with changes, shown in the text of this work, temperature 12,000°K, pressure 50 atm; 3 — according to [4] with changes, shown in the text of this work, temperature 12,000°K, pressure 50 atm.

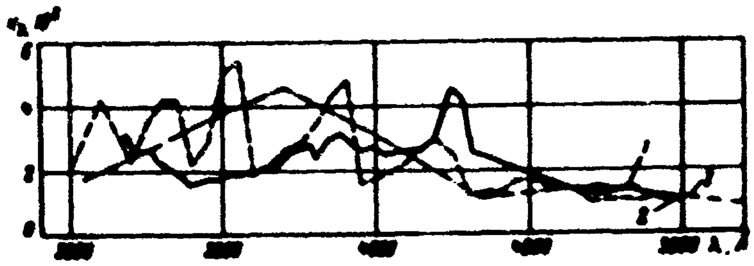

Fig. 12. Dependence of index of absorption of air on wavelength. 1 — experimental data of this work, temperature 10,500°K (pressure 50 atm); 2 — according to data of works [2, 3] with changes shown in the text of this work, temperature 10,000°K; 3 — according to [4] with changes shown in the text of this work, temperature 10,000°K.

Conclusion

1. Measurement was made of temperature of air, heated by a reflected shock wave in the range of Mach numbers of incident shock wave of 20-30. Up to Mach numbers of 24 sufficient agreement of experimental and calculation data has been established, for larger Mach numbers there is a systematic divergence of measured and calculated values of temperature, which, however, does not go beyond the limits of errors of measurement.

2. Comparison of experimentally measured and computed values of spectral indices of absorption of air made it possible to establish that in work [4] overstated values of absorption of the cross section of negative ion of nitrogen are accepted and, furthermore, in calculations [2, 4] overstated values of absorption of the cross section of the second positive system of nitrogen are accepted. In [12] are given calculations of indices of absorption of air in the temperature interval of 1000-24,000°K and densities of 10^{-6}-10^{1} from normal. A comparison of data from work [12] with data of [2, 3] showed that they are close based on their numerical values.

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