Radiation Measurements behind 8-12km/sec Shock Waves in Air and a $CO_2 + N_2$ Mixture

V.A. Volkov,* V.V. Zhurin,† A.B. Karasev,‡ B.K. Tkachenko§
Computing Center Academy of Sciences, Moscow, U.S.S.R.

Introduction

MANY previous experimental papers have dealt with equilibrium radiation from air, its components, and mixtures of $CO_2 + N_2$. Most of the spectral measurements have been performed with air at temperatures near 10^4 K and pressures at 1 atm. But the inconsistency in results of different authors is quite noticeable and much larger than the accuracy of the experiments. At higher temperatures for air and for mixtures of $CO_2 + N_2$, integrated spectral measurements have been made with a limited quantitative understanding about the processes responsible for the radiation.

The previous investigations were performed with arcs of different type stabilization[1-4] and behind the incident, reflected, and bow shock waves[5-8] in different type and size shock tubes. However, there is uncertainty in the air radiation values measured at temperatures of about 10^4 K and pressures of about 1 atm. For example, the results of Refs. 1,4, and 3 differ by a factor of approximately four. It is significant that none of the experimental results are lower than the continuum caused by atoms, molecules, and positive ions. In some papers there are attempts to explain the observed excess of the measured radiation beyond the calculated one by use of a negative Nitrogen ion. But there is no agreement on this.

For radiation from air and a mixture of $CO_2 + N_2$ at temperatures more than 1.5×10^4 K, one finds that the experiments are scarce and primarily measurements of integrated radiation were made.[9-11] The spectrum interval was in a range of 2000-6000 Å. Other measurements which should be noted are in Ref. 6 where the spectrum of air at a pressure of 24 atm was studied in the range of 3500-5500 Å. In calculations of plasma radiation with the temperature and pressure parameters increasing it is necessary to account for some important physical processes such as the optical and thermodynamic lowering of ionization potential. Spectral measurements at high pressures and temperatures are of great interest.

Apparatus

Radiation measurements for air and a mixture of $CO_2 + N_2$ were made using an electromagnetic shock tube with a diaphragm. The driven section was made of a stainless-steel tube with an inner diameter of 50 mm and was 4.5 m long while the driver section had an inner diameter of 30 mm and was 200 mm long.

A porous material served as a lining in the driver section. Just before the experiment water was poured into the lining, the driver gas, which was Helium, was heated by the disharge of condenser banks having 40-60 kJ energy. Before the experiment the inner surface of the driven section was carefully cleaned, pumped to 10^{-3} Torr, flushed and reevacuated several times, then filled with a test gas. Pressures studied in the driven section were in a range of 0.3-5 Torr.

Measurements of the continuum radiation intensity of air and a mixture of $CO_2 + N_2$ were provided by the photoelectric method at a wavelength of 5300 Å with a band interval of $\Delta\lambda = 10$ Å.

To find the spectral radiation distribution of shock heated gases, the spectral pictures were taken and the data reduced from those picture. A system of two fast shutters was installed in front of the spectrometer which was producing the photographic pictures with an exposure of 5-10 μsec. The shutters were opened in a time shorter than 1 μ sec. The first shutter was a small mirror whose covering could be evaporated by a condenser discharge initiated by the shock wave. The second shutter worked on a principle of heated wire expansion by the electric current, which was closing the spectrometer slit, passing through it.[12]

Such a photographic scheme made it possible to cut out the radiation from the contact region and the driver gas. Also during the experiment it was possible to calibrate the photographic film for an absolute sensitivity using a nine-step attenuator and as a result to increase the processing accuracy of the spectrum with heterochromatic photometry.

Experimental Results

Absorption coefficients obtained from the radiation measurements of air behind the incident shock wave at initial pressures of 1 and 2 Torr for shock wave speeds of $U_s = 7$-11 km/sec are shown in Fig. 1. The experimental values are in good agreement with those calculated[13,14] for temperatures up to 10^4 K, where the main contribution in a spectral interval

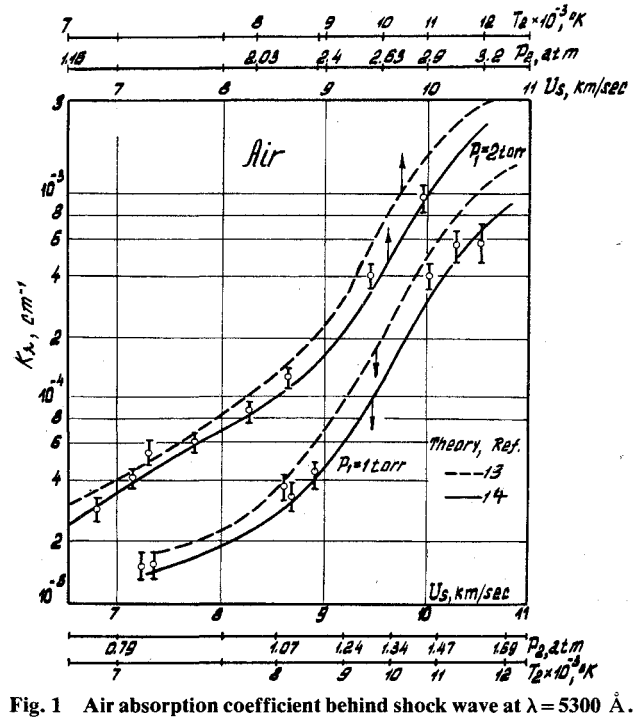

Fig. 1 Air absorption coefficient behind shock wave at λ = 5300 Å.

Received April 7, 1975; revision received Oct. 16, 1975.
Index categories: Radiatively Coupled Flows and Heat Transfer; Shock Waves and Detonations; Atomic, Molecular and Plasma Properties.

*Assistant Professor.
†Senior Research Scientist.
‡Professor.
§Associate Professor.

surrounding 5300 Å is from molecular radiation, electron-ion continuum radiation, and the so-called negative continuum radiation caused by photoattachment of electrons to Nitrogen and Oxygen atoms. The cross section of photodetachment for Oxygen was determined theoretically and was confirmed experimentally with a good certainty. Cross sections of $\bar{N}$ photodetachment have been determined experimentally by different authors using the scheme of subtracting the portion of the radiation caused by well-known processes from the total measured radiation; these cross sections were different from each other by a factor of several times. One of the reasons for the discrepancy may be that most experimental data were taken at atmospheric pressure where the expected magnitude of the contribution of $\bar{N}$ photodetachment is practically the same as the accuracy of a chosen experimental method and also within the uncertainties of the determination of the gas parameters. At high pressures when the $\bar{N}$ contribution should prevail over the other processes, the results of Ref. 6 did not support the expected values of the $\bar{N}$ continuum obtained from the experiments at atmosphere pressure. In our work the experimental values of the absorption coefficient for temperatures around 10^4 K and pressures of 1.5-3 atm were in a good agreement with those calculated in Ref. 14 where the N contribution was not taken into account. We believe this proves that the cross section of this process is a small one.

Figure 2 shows the absorption coefficients obtained from radiation intensity measurements at a temperature of 1.1×10^4 K for pressures of 1-60 atm. Experiments were made for both incident and reflected shock waves. We would like to emphasize that the values of absorption coefficient for a pressure of 3 atm were taken for both the incident and the reflected shock waves and were in a good agreement with each other and thus testify on the equality of the gas parameters. The comparison of calculations in Refs. 13 and 14 with the experimental results of different authors indicates there is a small photodetachment cross section for $\bar{N}$.

Figure 3 presents the air radiation absorption coefficient spectrum in the visible region for a reflected shock wave with a speed of $U_s=7.3$ km/sec and an initial pressure of $p_1=2$ Torr. Calculated values of temperature and pressure were 1.3×10^4 K and 28 atm, respectively. Exposure time was 8 μ sec and the spectrometer slit width was 0.2 mm. The dark-counts of the photomultipliers were taken during the experiments. Processing was performed by heterochromatic

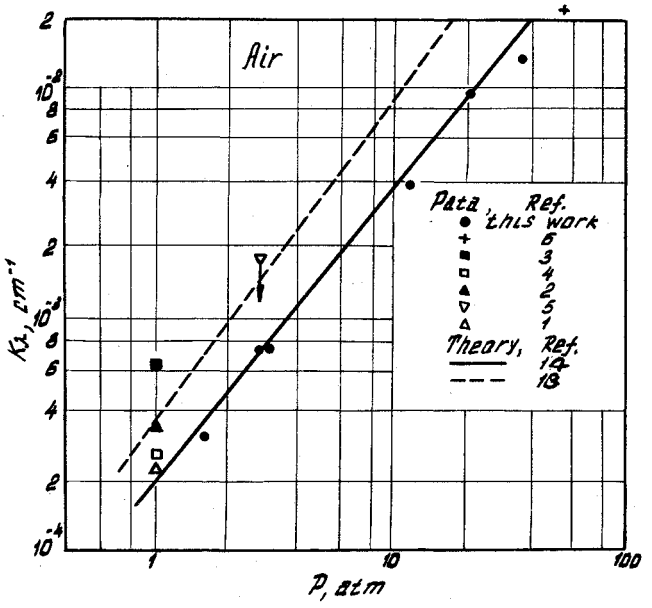

Fig. 2 Air absorption coefficient (theory and experiments) at $T=1.1\times 10^4$K and $\lambda=5300$ Å and different pressures behind shock wave.

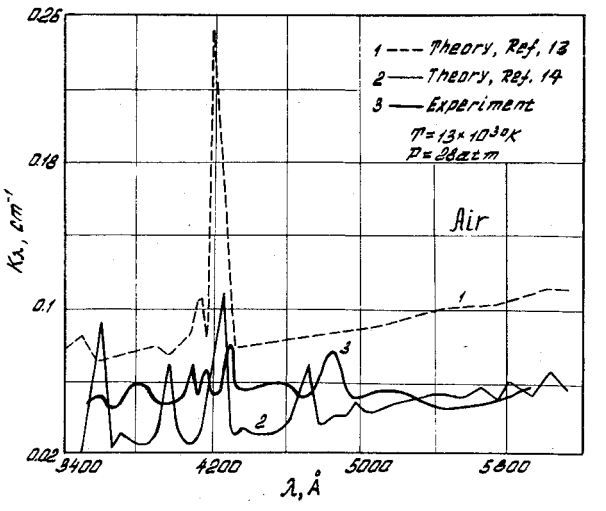

Fig. 3 Air absorption coefficient spectral distribution behind reflected shock wave at $T=1.3\times 10^4$K and $p=28$ atm.

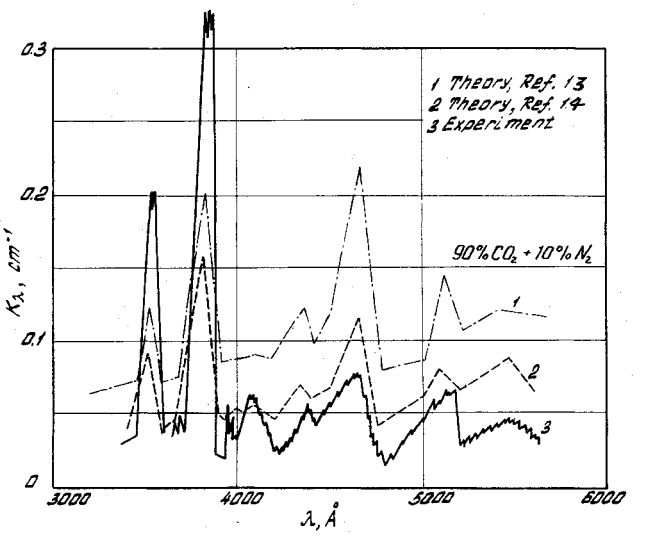

Fig. 4 Absorption coefficient spectral distribution for mixture 0.9 $CO_2+0.1$ N_2 behind reflected shock wave at $T=1.2\times 10^4$ K and $p=44$ atm.

photometry. The sensitivity of the spectrum film was determined by a calibrated band lamp. Normalization for absolute values as performed by photoelectric measurements at a wavelength of 5300 Å.

In this spectrum of the region 3500-6000 Å, it was possible, as opposed to Ref. 6, to observe the group of lines NI in the region 4100-4300 Å which were taken into account in the calculations of Refs. 13 and 14. The curve of the spectral absorption coefficient of air is qualitatively consistent with those calculated using the proper aperture correction for the Nitrogen lines.

Figure 4 presents the spectral absorption coefficient of a 0.9 $CO_2+0.1$ N_2 (mole fractions) mixture. For the reflected shock wave with $p_1=2$ Torr and $U_s=7.05$ km/sec, the equilibrium calculated parameters were 1.2×10^4 K and 44 atm. The spectrum interval was 3500-6000 Å. Analysis of the spectrum was performed in the same manner as for air radiation. To find the absorption coefficient in the cants of molecular bands CN and C_2, the spectrum was taken for layers of thickness 1 cm and 5 cm. Normalization of other parts of the spectrum was provided by photoelectric measurements at a wavelength of 5300 Å. As is seen from the spectrum, the radiation in the visible region is determined by systems $CN(B^2\Sigma^+-X^2\Sigma^+)$ and C_2 $(d^3\Pi g-a^3\Pi u)$. In the same figure the calculated curves are presented with account taken for the molecular radiation CN and C_2, *CI*

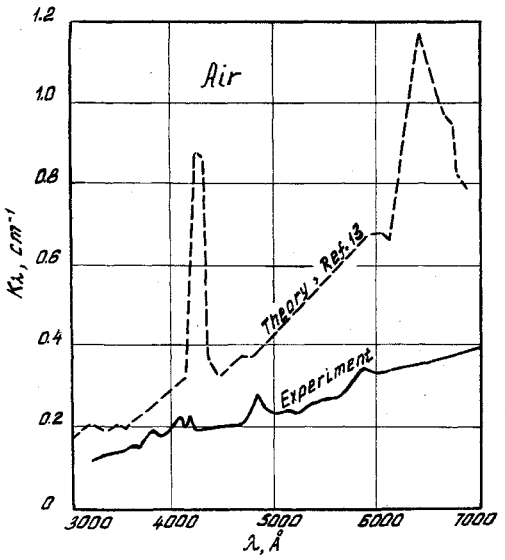

Fig. 5 Air absorption coefficient spectral distribution behind reflected shock wave at $T = 1.78 \times 10^4$ K and $p = 46$ atm.

photoionization and free-free transitions in the C^+ electric field and also the radiation caused by $\bar{O}$, $\bar{C}$, and $\bar{N}$ photodetachment. For comparison there is a curve which does not account for $\bar{N}$.

In the calculation of gas parameters the value of dissociation energy D_0 $(CN) = 7.5$ eV was used. But from the spectrum, one could find the value D_0 $(CN) = 7.9 \pm 0.1$ eV. The molecular absorption coefficients of C_2 are in good agreement with those calculated.

The absorption coefficient results of radiation measurements for air at high temperatures ($T \gtrsim 1.6 \times 10^4$ K, $p \gtrsim 30$ atm) where the electron continuum predominates, showed the values to be lower than those calculated using the Biberman-Norman theory. In particular at 1.8×10^4 K and 46 atm (Fig. 5) the experimental values are 1.5-2 times lower than those calculated. The optical ionization potential lowering used in the calculations is 0.7 eV. The uncertainty in this value does not explain the experimental and theoretical discrepancy since for satisfactory agreement ΔU optical should be equal to zero. However, at conditions of this experiment, the electron density is very high, $N_e > 10^{18}\text{cm}^{-3}$, and thus one would not expect ΔU optical to be zero.

In order to calculate the gas properties, the air thermodynamic parameters of Ref. 15 were used. In recent author's paper[16] it was found good agreement of measured and calculated[15] parameters for strong reflected shock waves in air.

References

[1]Boldt, G., "The Recombination and "Minus" Continua of Nitrogen Atoms," *Zeitschrift für Physik*, Vol. 154, 1959, pp. 330-338.

[2]Morris, J.C., Bach, G.R., Krey, R.U., Liebermann, R.W., and Yos, J.M., "Continuum Radiated Power for High Temperature Air and Its Components," *AIAA Journal*, Vol. 4, July 1966, pp. 1223-1226.

[3]Asinovsky, E.I., Kirillin, A.V., and Kobsev, G.A., "Analysis of Continuous Nitrogen Plasma Radiation," *Journal of Quantitative Spectroscopy and Radiative Transfer*, Vol. 10, March 1970, pp. 143-164.

[4]Andreev, G.F., Grankova, D.A., Ershov-Pavlov, E.A., Kiselevsky, L.I., Shimanovich, V.D., "Spectral Radiation of Nitrogen plasma at Atmosphere Pressure and Temperature Region 9000-16500 °K," *Journal of Applied Spectroscopy*, USSR, Vol. 14, May 1971, pp. 916-918 (in Russian).

[5]Thomas, G.M. and Menard, W.A., "Measurements of the Continuum and Atomic Line Radiation from High Temperature Air," *AIAA Journal*, Vol. 5, Dec. 1967, pp. 2214-2223.

[6]Konkov, A.M., Riazin, A. P., and Rudnev, V.S., "The Experimental Determination of the Absorption Coefficient of Air at 10000-12000°K," *Journal of Quantitative Spectroscopy and Radiative Transfer*, Vol. 7, No 2, 1967, pp. 345-352.

[7]Vakatov, V.P., Volkov, V.A., Danilov, A.S., Karasev, A.B., Maliavin, V.P., Tkachenko, B.K., "Experimental Investigation of Air Optical Properties and Mixture $CO_2 - N_2$ at Temperatures 8000-19000°K," *Proceedings of Third All-Union Conference on Low Temperature Plasma*, Moscow, pp. 168-172, 1971 (in Russian).

[8]Ciffone, D.L. and Borucki, J.G., "Spectral Measurements of Nitrogen Continuum Radiation behind Incident Shocks at Speeds up to 13 km/sec," *Journal of Quantative Spectroscopy and Radiative Transfer*, Vol. 11, Sept. 1971, pp. 1291-1310.

[9]Nerem, R.M. and Stickford, G.H., "Radiative and Convective Heating during Hypervelocity Re-Entry," *AIAA Journal*, Vol. 2, June 1964, pp. 1156-1158.

[10]Fairbairn, A.R., "Spectrum of Shock-Heated Gases Simulating the Venus Atmosphere," *AIAA Journal*, Vol. 2, June 1964, pp. 1004-1007.

[11]Menard, W.A., Thomas, G.M., and Helliwell, T.M., "Experimental and Theoretical Study of Molecular Continuum and Line Radiation from Planetary Atmospheres," *AIAA Journal*, Vol. 6, April 1968, pp. 655-1664.

[12]Camm, J.C., "High Speed Spectrograph Shutter," *The Review of Scientific Instruments*, Vol. 31, March 1960, pp. 278-279.

[13]Avilova, I.V. , Biberman, L.M., Vorobiev, V.S., Zamalin, V.M., Kobzev, G.A., Lagarkov, A.N., Mnatcakanian, A.Kh., Norman, G.E., "Optical Properties of Hot Air," Moscow, 1970 (in Russian).

[14]Kamenshikov, V.A., Plastinin, Iu. A., Nikolaev, V.M., Novitcki, L.A., "Radiative properties of Gases at High Temperatures," Moscow, 1971 (in Russian).

[15]Predvoditelev, A.S., Stupochenko, E.V., Pleshanov, A.S., Samuilov, E. B., Rozhdestevensky, I.B., "Tables of Air Thermodynamic Functions," Moscow, 1959 (in Russian).

[16]Zhurin, V.V., Alipov, S.V., Karasev, A.B., Tkachenko, B.K., Volkov, V.A., "Strong Shock Wave Reflections Study," Proceedings of the Tenth International Shock Tube Symposium, Kyoto, Japan, July 1975, pp. 742-755.