SOME TECHNIQUES FOR PHYSICAL EXPERIMENTS IN A SHOCK TUBE WITH A NOZZLE

I. E. Zabelinskii, S. A. Losev, and O. P. Shatalov

UDC 533.6.071.8+539.107+539.196

The authors describe a technique for experiments in a shock tube with a nozzle: operation of the high-pressure chamber, the pumping system, measurements of velocity and pressure, and absorption measurements in the nozzles.

Nowadays there has accumulated a rich experience in operations in shock tubes and a large volume of experimental data has been obtained in the field of physical gasdynamics and kinetics of relaxation processes at high temperature. In addition to journal articles, part of this information appears in monographs [1-3]. Meanwhile the areas of application of shock tubes are expanding, and effects that are new in principle have been observed; for example, recently rarefaction shock waves have been obtained for the first time [4, 5]. One imposes increasing requirements on the conduct of experiments in shock tubes, on the uniformity of the flow, reproducibility of results, reduced scatter of experimental data, and therefore, on the accuracy of measuring the initial parameters and parameters recorded in the flow, the quality of diaphragm opening, monitoring of lifetime of the unperturbed flow behind the shock wave front, both incident and reflected (if we are dealing with experiments with a reflecting wall or in a nozzle), etc. Experimenters unavoidably devote considerable attention [6, 7] to analysis of these matters, but the accumulated experience usually remains within the scientific publications.

This paper contains some material on technique, accumulated during the investigation of excitation, deactivation, and recombination of molecules of oxygen and carbon dioxide, as well as on resolution of a number of other problems in a shock tube with a nozzle [8-10]. There are undoubtedly many other interesting solutions and a rich experience of technique deriving from investigators operating in shock tubes, and the exchange of this experience is, in our opinion, not only useful, but necessary.

Shock Tube. The experiments were conducted in a shock tube which had a high-pressure chamber (HPC) with an inside diameter of 90 mm and length 3 m, and a low-pressure chamber (LPC) with inside diameter 493 mm and length 12 m [8-10]. The chambers were connected via a machined conical transition piece, and separating the two chambers was an aluminum or copper diaphragm of thickness 1-2 mm.

At a distance of 1.5 m from the end of the LPC there was a two-dimensional wedge-shaped nozzle with a reflecting wall. The apart ahead of the nozzle is practically a forechamber containing gas at rest with parameters corresponding to those of the wave reflected from the nozzle wall. These parameters are very often calculated by standard methods (see, e.g., [1, 2, 11]), and are input parameters for the conduct and data processing of the nozzle experiment. The nozzle can be moved relative to the viewing windows in the shock tube walls, so that one can take measurements at different distances from the throat. During investigation of processes behind the incident shock wave front the nozzle was removed from the shock tube.

The driver gas was either simply compressed hydrogen or helium, or an oxygen–hydrogen mixture, heating during detonation of the driver gas + diluent (oxygen or nitrogen). In the first case, to ensure reproducibility of results and reliable diaphragm opening and avoid flight of fragments we mounted cruciform blades of solid steel at a distance of 2-3 mm ahead of the diaphragm. When the HPC was filled with gas the diaphragm bulged, was pressed against the blades, and with their help opened into four petals. The diaphragm opening pressure was

Institute of Mechanics of the M. V. Lomonosov Moscow State University. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 48, No. 3, pp. 357-364, March, 1985. Original article submitted November 9, 1983.

0022-0841/85/4803-0249$09.50

controlled here both by the diaphragm thickness and material, and by the gap between the diaphragm and the blades. By using rather sharp blades and diaphragms made of material from a single batch one achieves high reproducibility of shock wave speed. The diaphragm was fastened in a special cassette with a hardened annular notch, to ensure mechanical strength of the mounting and vacuum sealing of the chambers.

HPC with Detonating Mixture: Diaphragms, Filling, Ignition System. The requirements of a broad range of parameters attainable in the facility leads to the need to use in the HPC a stoichiometric mixture of oxygen and hydrogen, in 70-80% of diluent driver gas (hydrogen, helium, nitrogen or a mixture of these). As was noted earlier in [12], with lesser amounts of diluent in the chamber the detonation is broken up, leading to a sharp and poorly reproducible increase of driver gas pressure; but with large diluent concentrations the mixture does not always ignite. With a detonating mixture in the HPC one should use the blades, and calibrated grooves cut or milled on the diaphragm, of depth 0.3-1.5 mm. This kind of diaphragm withstands a pressure only a few atmospheres greater than the initial value of the gas in the HPC, which usually varies in the range 5 to 40 atm. With the aid of a type LKh piezoelectric sensor mounted on the side wall of the HPC it was established that after ignition of the detonating mixture the gas pressure proceeded to rise and hold at constant level for some time, after which the diaphragm opened, i.e., the mixture burned without change of volume. The driver gas pressure then increased by a factor of 7-10, and the diaphragm opened into petals strictly following the grooves. In this regime of operation the reproducibility of shock wave speed is quite satisfactory — the scatter does not exceed 30-50 m/sec, and is not determined by the nature of the grooves or the quality of the material, but by the accuracy of filling the HPC with the gas mixture (by the pressure), the quality of mixing of these gases, and the operation of the ignition spark plugs. With a detonating mixture one can smoothly vary the shock wave speed over a wide range by varying the driver gas pressure. In addition, by partially or completely replacing the hydrogen of the heated detonating mixture in the HPC by nitrogen one can smoothly reduce the shock wave speed.

As was noted earlier, when operating with a detonating mixture in the HPC it is important to avoid the development of detonation (unless the chamber is specially constructed, of course, for operation in the detonation regime). A detonation front can be formed if the mixture is poorly mixed and it is ignited at a single point, e.g., at the end of the chamber, and the length of the chamber is great enough (more than 0.5 m). To avoid detonation, it is desirable to admit each component of the gas mixture into the HPC at several points along the length and to ignite the mixture simultaneously at several points also. To do this we set up 6 automobile spark plugs in a spiral along the entire length of the HPC, operated from a pulse ignition unit. Simultaneous sparking of the plugs was achieved with the aid of a shock (microsecond) pulse produced by a trigger pulse circuit. The circuit was based on type KU 202N and TChI-900/12 thyristors. A voltage of 1.0-1.5 kV was supplied to the primary windings of pulse transformers. At the secondary windings of the transformers, wound on ferrite cores, appeared at voltage of 30-40 kV, leading to breakdown of the spark plug gap. The plugs were recessed somewhat in the walls of the HPC, to protect them from premature disintegration: they lasted for several hundreds of experiments, although the working pressure often exceeded a hundred atmospheres. A sign of failure of the plugs in the HPC was a jump in the shock wave speed, sometimes accompanying removal of the diaphragm.

Low-Pressure Chamber: Pumping, Filling. In the resolution of a number of problems in shock tubes, primarily kinetic matters, the main defect is using a detonating mixture as the driver gas is the formation of water vapor. In cases where this factor is not significant, the speed capability of the facility does not differ from that of a tube with the usual driver gas, the range of available speeds is wider, and the flow rate of gases is considerable less. However, in the investigation of kinetic processes, e.g., in the study of relaxation of O_2 or CO molecules, dissociation of CO_2, etc., even a small water vapor impurity (in excess of 0.01-0.02%) can appreciably distort the process being investigated, due to fast exchange reactions with hydrogen-containing particles, and vibrational relaxation at H_2O molecules [13, 14]. In that case one must take special steps to eliminate water vapor from the facility and to monitor its content. Besides the methods customarily used in such cases, such as flushing the facility with dry gas or with the test mixture, it is desirable to mount (liquid) nitrogen traps in the vacuum lines, and to do the pumping with two pumps: one pump to remove the main mass of water vapor, along with other gases remaning after the shot, and also to pump out atmospheric air after changing the diaphragm, and a second pump for finally reaching the required vacuum in the LPC. Nitrogen traps absorb water vapor remaining in the tube

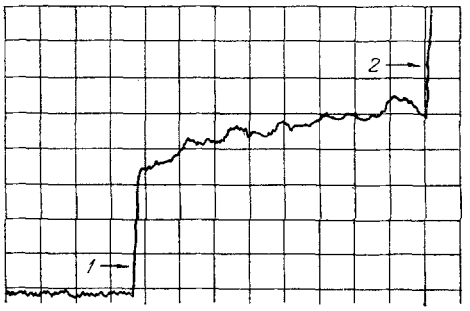

Fig. 1. Specimen of recorded signals from speed measurement sensors: 1, 2) signals from the first and second film sensors, respectively (upon passage of the shock wave). One division is 10 μsec.

with high efficiency. The shock tube described was pumped down using only forevacuum pumps, to a pressure of $(1-2)\cdot10^{-2}$ torr; the leak rate of the LPC due to inadequate sealing and desorption of gases from the walls after pumping down and chilling was $(4-5)\cdot10^{-5}$ torr/min. The concentration of water vapor impurity estimated from this leak rate in the test gas was less than 0.01%. Before the experiment the LPC was washed with the test gas and then filled to the required pressure. The gas pressure was measured with the aid of diaphragm and oil manometers to an accuracy of not worse than 0.2%.

It is convenient to monitor the process of filling the LPC of the shock tube with test gas with the aid of commercial type MAS-ÉZ absolute pressure manometers. These electromechanical pressure transducers, with digital output signal, operating, in particular, in the pressure range 0-45 torr are not of a high accuracy class (2.5%), but each individual instrument can be calibrated with an oil manometer, to an accuracy not worse than 1%. We note that there are piezooptical pressure transducers [15] offering considerably higher pressure measurement accuracy.

Measurement of the Shock Wave Speed. It is convenient to record the speed of propagation of the shock wave by means of two thermal (film) sensors, mounted on a single removable insert in the side wall of the measuring section. By mounting the sensors on a removable insert one can measure the distance between the sensor films to a high accuracy (better than 0.1%). This distance was about 100 mm for the different sensor pairs.

The signals from the film sensors, arising on passage of the shock wave front, in our experiments came to the input of type DL-922 and DL-4000 transient process recorders, which have a frequency resolution of 20 MHz, a digital memory, sweeps calibrated by a quartz oscillator, and can display the recorded signals on the screen or on a graph plotter. Taking into account the uncertainty arising in the case when a signal arrives at the moment when information is stored in two adjoining cells of memory, the finite width of the sensor films, and the finite curvature of the front of the signals, the error in measuring the shock wave speed was estimated to be not worse than 0.5%. An example of signals recorded from the sensor films is shown in Fig. 1. Naturally, these signals can be recorded with ordinary oscillographs or frequency meters having the required sensitivity and frequency characteristics.

Pressure Measurement. In the side wall of the measuring section we located several piezoelectric pressure sensors [16]. They were placed both along a diameter, and along the section, so that, besides the pressure, they could also measure the shock wave speed, although with less accuracy than when the film sensors are used, because of the larger size of the latter (diameter 3-4 mm). The main purpose in installing the piezoelectric sensors was to obtain information on the pressure and lifetime of the unperturbed reflected wave before it entered the nozzle. Figure 2 shows specimen signals from piezosensors mounted in the side and end walls of the shock tube. In the range of initial conditions that we investigated the equilibrium gas pressure behind the incident shock front, calculated from the known conservation laws and the equation of state, varied in the range 0.3-3.6 atm. These data were used to calibrated the sensitivity of the piezoelectric sensors. The accuracy in determining their sensitivity was ±3%. After calibration the sensors were used to measure the pressure

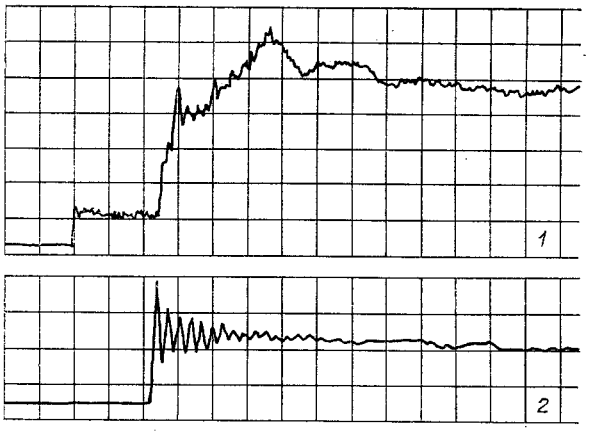

Fig. 2. Specimen signals of the piezosensors measuring the pressure in the reflected shock wave: 1) sensor in the tube side wall, v_1 = 1906 m/sec, P_1 = 0.0244 atm, 1 cm = 50 μsec; 2) sensor in the end wall, v_1 = 2072 m/sec, P_1 = 0.01 atm, 1 division is 40 μsec.

in the reflected shock wave, and for this purpose some were mounted in the side wall, and some in the reflecting end wall, and recorded the pressure only in the reflected shock wave. Each sensor mounted in the tube end wall, following a certain period of initial "ringing" with a self-frequency of about 300 kHz, systematically recorded a constant gas pressure level prior to entry into the nozzle, maintained for several hundreds of microseconds. The pressures measured with the end wall sensors indicated that the equilibrium gas pressure in the reflected shock wave, as calculated from the initial gas pressure in the tube and the speed of the incident shock wave, coincides with the results of direct measurement of this pressure at the end of the shock tube. No systematic decrease or increase of the gas pressure at the end of the shock tube relative to the theoretical value was observed during the lifetime of the unperturbed slug of reflected gas. The experiments were conducted with oxygen in the incident shock speed range 870-2700 m/sec, and the rms error in pressure measurement at the end wall was about 6%.

The signal from the side-wall sensor describes the arrival of both the incident and the reflected shock wave, and is more complex (see Fig. 2). Immediately following the "plateau" describing the pressure in the incident shock wave there is a characteristic peak and amplitude comprising 30-60% of the pressure in the reflected shock wave, after which the pressure again increases, but occasionally remains constant. In fact, the side-wall sensor does not measure the pressure in the reflected shock wave, but the result of its interaction with the boundary layer, the development of bifurcation, the pressure under the λ-foot, smearing of this λ-foot as the wave moves, and so on (see [3, 10] for more details of this). The true picture of the pressure variation in the reflected shock wave is then distorted, and the side-wall sensor records a certain total effect of all the interactions. It is not possible then to measure the pressure in the reflected shock wave using sensors in the side wall with an accuracy of better than ±15-20%.

Absorption Technique. We used the traditional method of absorption spectroscopy to investigate the rate of deactivation of oxygen excitation in a two-dimensional wedge-shaped nozzle. The light source was a type LOS-2 instrument which uses a type DKSSh-1000 high-pressure quartz lamp, filled with xenon and supplied with 30-75-A dc. The probing radiation from the lamp passed through quartz windows (or slits) in the shock tube, and reached the entrance of a type ZMR prism monochromator with dispersion of 1.0 nm/mm, and was subsequently recorded by a photomultiplier. From the lamp continuum the monochromator selected radiation at λ = 210 or 230 nm, for which the absorption was investigated in this study. The radiation detector, a type FÉU-99 "blind" photomultiplier, has a sensitivity range of 160-360 nm. By using it we are practically free from scattered visible light, which is a real obstacle in performing an absorption experiment in the UV spectral range. The signal from the photomultiplier reached the recorder input (a type DATALAB transient process recorder) and was then retained in the memory of these instrument or was recorded on a graph plotter. The timewise resolution

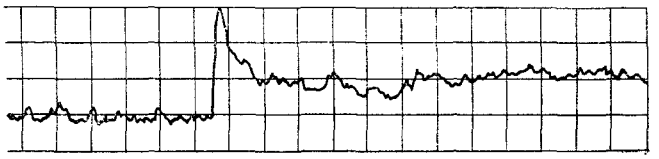

Fig. 3. Absorption of λ = 230 nm radiation by oxygen molecules in a two-dimensional wedge-shaped nozzle (the nozzle opening angle is 15°, the throat width is 4 mm) during discharge of gas from the region behind the reflected shock wave at a distance of 32 mm from the throat. The initial oxygen pressure is 0.014 atm, and the incident shock speed is 1990 m/sec. One division is 40 μsec.

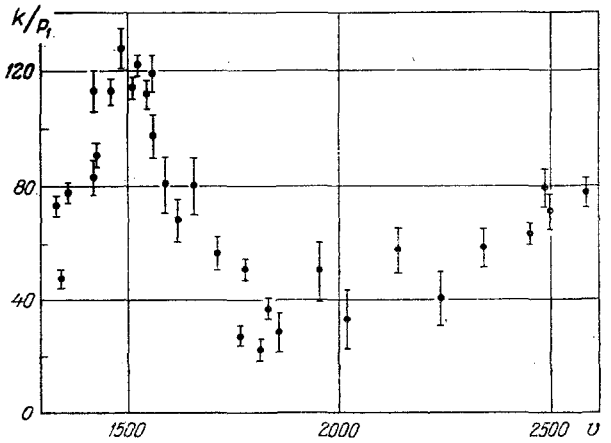

Fig. 4. The absorption coefficient at λ = 230 nm by molecular oxygen as a function of incident shock speed in the conditions of Fig. 3, at a distance of 73 mm from the nozzle throat. The absorption coefficient is referenced to the initial gas pressure ahead of the shock ($P_1 \approx 6.1$ torr), v, m/sec, k/P_1, $m^{-1} \cdot atm^{-1}$.

of this recording channel, accounting for the shock tube slit width and the transfer characteristics of the cables, was not worse than 1 μsec.

The experiments to measure absorption of radiation in the nozzle were conducted at a distance of 20-80 mm downstream from the nozzle throat. The nature of the oscillograms was always the same (Fig. 3): after an initial flash characteristic of the nozzle "starting" (see [3] for more detail on this), a constant level of absorption signal was observed, corresponding to steady discharge of the vibrationally excited oxygen, which is partially dissociated at the higher temperatures. The absorbed light fraction was determined in accordance with Beer's law of concentrations and the vibrational state of the absorbing particles:

$$A = 1 - \exp(-kl) = 1 - \exp(-n\sigma(T_k)l).$$

It was shown earlier in [17] that this law can be used over a wide range of concentrations and wavelengths. (Here A is the fraction of the probing radiation absorbed by the gas; n is the number density of absorbing molecules; l is the optical path length in the absorbing medium, 49.3 cm in our conditions; and $\sigma(T_k)$ is the effective absorption cross section in the $\Delta\lambda$ interval investigated.)

The results of measuring the absorption coefficient of λ = 230 radiation by molecular oxygen in the nozzle at a distance x = 73 mm from the throat are shown in Fig. 4 as a function of the incident shock speed. The initial gas pressure in this series of experiments was

close to a constant value of $P_1 \approx 0.008$ atm, and only the shock speed was varied. The substantially nonmonotonic behavior of the absorption coefficient stems from the different mechanisms which affect it as the temperature increases. At low shock speeds (up to 1500 m/sec) the absorption in the nozzle increases with increasing incident shock speed, and with increase of gas temperature at the nozzle entrance. This part of the curve is determined by the rate of deactivation of excitation of the oxygen molecules in O_2–O_2 collisions during discharge from the nozzle. For v > 1500 m/sec, O atoms appear in the reflected shock wave prior to entry into the nozzle, and the rapid deactivation of vibrations of oxygen molecules in the nozzle on interaction with these atoms leads to a fall in the vibrational temperature of the molecules, and a corresponding fall in the observed absorption. Further increase of the incident shock wave speed (above 1700-1800 m/sec) leads to a new growth of absorption in the nozzle, due to processes of recombination of atoms and further increase of the vibrational temperature of the molecules. The final objective of this investigation is a correct description of the observed absorption in the entire range of initial conditions investigated. To do this we need information on the rate constants of the physical and chemical processes occurring in the conditions of the flow examined, and in many cases we must account for the mutual influence of these processes.

Conclusions. If we turn to any handbook of rate constants of physical and chemical reactions, it is easy to verify that the scatter of these constants exceeds, by an order of magnitude, the rms error assigned by each author. Many of these errors are due not only to the use of an inadequate mathematical model of the phenomenon investigated, but also to errors of technique that were not monitored, and were often even unknown to the authors, e.g., the presence of impurities in the gas, light scattered into the recorded radiation, and systematic errors in measuring velocity, pressure, and so on. In our opinion, if the experimenters calculated the special features of their technique enumerated here when conducting investigations in shock tubes they could to some extent reduce the systematic errors in the measured quantities that are not amenable to analysis.

LITERATURE CITED

1. E. V. Stupochenko, S. A. Losev, and A. I. Osipov, Relaxation Processes in Shock Waves [in Russian], Nauka, Moscow (1965).
2. A. Gaydon and I. Hurl, The Shock Tube in High Temperature Chemical Physics [Russian translation], Mir, Moscow (1965).
3. T. V. Bazhenova and L. G. Gvozdeva, Unsteady Interactions of Shock Waves [in Russian], Nauka, Moscow (1977).
4. S. S. Kutateladze, Al. A. Borisov, A. A. Borisov, and V. E. Nakoryakov, "Experimental observation of a rarefaction shock wave near the liquid-vapor critical point," Dokl. Akad. Nauk SSSR, 252, No. 3, 595-598 (1980).
5. Ya. B. Zel'dovich, S. S. Kutateladze, V. E. Nakoryakov, et al., "Observation of a rarefaction shock wave near a liquid-vapor critical point," Nauchnoe Soobshch., Vestn. Akad. Nauk SSSR, No. 3, 3-8 (1983).
6. C. P. Schneider and G. Hahne, "Effect of shock tube cleanness on the initial ionization rate of an argon plasma," Proc. 12th Int. Symp. on Shock Tubes and Waves, Jerusalem (1979), pp. 222-231.
7. B. K. Tkachenko, "Special features of high temperature flows in shock tubes, and the scatter of the experimental data," in: High Temperature Gasdynamics, Shock Tubes and Shock Waves. Rep. Int. Sem., Ed. R. I. Soloukhin, Minsk: Inst. Heat and Mass Trans. im. A. V. Lykov, Akad. Nauk SSSR (1983), pp. 46-51.
8. V. N. Makarov and O. P. Shatalov, "Vibrational Deactivation of Molecular Oxygen in a cooled flow," Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 2, 184-188 (1974).
9. A. B. Britan, S. A. Losev, V. N. Makarov, et al., "Deactivation of vibrational states of carbon dioxide molecules in a cooling flow," Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 2, 204-205 (1976).
10. A. B. Britan and A. P. Mazmanyants, "Investigation of the gasdynamic characteristics of a large diameter shock tube with a nozzle," Nauchn. Trudy Inst. Mekh. Mosk. Gos. Univ., No. 43, 28-47 (1976).
11. C. K. Law and M. Bristow, "Tables of normal shock wave properties for oxygen and nitrogen in dissociation equilibrium," UTIAS Techn. Note No. 148 (1969).
12. S. C. Lin and W. I. Fyfe, "Low-density shock tube for chemical kinetics studies," Phys. Fluids, 4, No. 2, 238-249 (1961).

13. I. E. Hardy, W. C. Gardiner, and A. Bureat, "Recombination of CO and O atoms," Int. J. Chem. Kinet., 10, No. 8, 503-517 (1978).
14. I. S. Zaslonko, "Molecular reactions in shock waves and energy transfer in highly excited molecules," Author's Abstract of Candidate's Dissertation, Physical and Material Sciences, Moscow (1981).
15. I. I. Slezinger, "Piezoelectric measuring transducers. Measuring transducers," Mezhvuz. Sbor. Nauch. Trud. Ed. V. Ya. Lozhnikov, Omsk: Omsk Polytechnic Institute (1979), pp. 139-149.
16. Inventor's Certificate No. 317928, "Piezoelectric pressure sensor," No. 2141, G. N. Suntsov, Byull. Izobret., No. 31 (1971).
17. V. K. Dushin, I. E. Zabelinskii, and O. P. Shatalov, "Effective cross sections for absorption of UV radiation by O_2 molecules over a wide temperature range," Zh. Prikl. Spektrosk., 39, No. 3, 440-443 (1983).

SPECIFIC POWER OUTPUT OF A GASDYNAMIC CO_2 LASER WITH NOZZLES OF WEDGE AND CONTOURED GEOMETRIES

S. B. Goryachev, N. M. Efremov,
V. T. Karpukhin, N. B. Rodionov,
S. M. Chernyshev, and V. F. Sharkov

UDC 621.375.826

The results of an investigation of the specific power output of gasdynamic CO_2 lasers with nozzles of different constructions are presented and the prospects for their use in technological equipment are discussed.

The results of theoretical and experimental research on gasdynamic CO_2 lasers (CO_2 GDL) obtained up to now and presented in a number of works [1-3] can in principle serve as a good foundation for the practical construction of test laser technological equipment (LTE) [4]. At the same time, in the creation of continuous LTE of this type a number of specific engineering problems arise, the solution of which determines the possibility of their technical realization to a considerable extent.

One of the most important problems in the creation of LTE is to provide a nozzle apparatus with a long continuous operating life. For the range of working temperatures of the gas mixture required in practice, $T_0 \approx 1600$-$2000°K$, the primary requirement evidently is the development and fabrication LTE nozzles with cooled constructions. The operation of a test technological GDL with a cooled nozzle apparatus is reported in [4], where it is shown that a technically simple and reliable system for efficient nozzle cooling can be realized only for sufficiently large-scale mononozzles at present. But a complex technical solution is required to implement a system for cooling a large number of small nozzles, which comprise the most promising GDL nozzle apparatus based on the recommendations of the physical research of [1, 2].

In the first stage of work on continuous LTE one can evidently recommend only the simplest constructions for the nozzle apparatus, consisting of large mononozzles with a simplified supersonic contour, of wedge profile, for example, which allow one to provide their efficient cooling and hence the capacity to operate for a long time. Such LTE make it possible even now to solve a number of the problems connected with the study of the peculiarities of the application of laser radiation in industry [5, 6]. Of course, the feasibility of such equipment depends primarily on how much one can reduce the losses of stored energy in nozzle apparatus of simplified construction as compared with the optimum nozzle arrays.

Institute of High Temperatures, Academy of Sciences of the USSR, Moscow. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 48, No. 3, pp. 364-369, March, 1985. Original article submitted January 3, 1984.

0022-0841/85/4803-0255$09.50