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High-power repetitively pulsed CO_2 laser with mechanical *Q*-switching and its application to studies in aerodynamic installations

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Abstract. **A new method for organising the repetitively pulsed regime of CO_2 laser oscillation at the expense of a self-filtering resonator and two concave cylindrical mirrors with equal curvature in the intracavity modulator is considered. The studies of the energy and temporal characteristics of the laser radiation show that the constructed laser has high efficiency close to that of a cw laser. The mean and pulse power of 4.5 and 200 kW, respectively, are obtained. For a wide range of gas-dynamic characteristics the possibility of the optical breakdown in the supersonic wide-aperture air flow is demonstrated. The coefficient of absorption of laser radiation in optical breakdown plasma in a supersonic air flow is investigated and its value amounting to 60 % is obtained. For the first time it is found that the threshold density of air, corresponding to the efficiency jump, is equal to 1.8 – 2 kg m^{-3} and independent of the Mach number M = 1.7 – 3.7.**

Keywords: *high-power repetitively pulsed CO_2 laser, mechanical Q-switching, supersonic air flow, air optical breakdown, plasma absorption coefficient.*

1. Introduction

Construction of lasers operating in the repetitively pulsed regime with the pulse repetition rate up to 100 kHz and the pulse power substantially (nearly 100 times) higher than the mean power allows considerable expansion of the laser radiation application filed, increased efficiency of its use and implementation of qualitatively new effects. A prospective study is devoted to the action of laser radiation on the supersonic gas flow [1, 2] as well as to the aerospace applications [3, 4]. The introduction of radiation into the gas flow may be implemented using a continuous optical discharge (COD), proposed by Yu.P. Raiser [5]. However, the studies have shown that such a discharge cannot be produced at flow velocities exceeding a few tens of meters per second [6, 7]. In Ref. [8] a pulsed optical discharge (POD) was obtained that was ignited in the focus of the radiation beam from a repetitively pulsed CO_2 laser in a supersonic argon jet. The influence of such a discharge on the jet is analogous to that of the COD. To produce a POD in supersonic air flows in the course of experiments with real supersonic wind tunnels, the required radiation powers exceed by an order of magnitude the power of the laser used in the argon experiments. The creation of such a laser offers the challenge of studying the POD in the air at Mach numbers $M > 1$ [9].

A successful line of development, related to the goal of getting high-power repetitively pulsed radiation, is the use of optomechanical modulation of losses in the resonator of a CO_2 laser. The authors of [10] used the gain modulation of the active medium by self-injection of radiation into an unstable resonator. The possibility to put a high-power wide-aperture CO_2 laser into operation in the repetitively pulsed regime was demonstrated. However, the generated radiation had the form of a train of pulses with a wide spread of peak powers that were 6.5 – 11 times higher than the mean power.

It looks promising to obtain the repetitively pulsed regime of CO_2 laser oscillation [8] using the self-filtering resonator. This is a confocal resonator [11, 12] consisting of two confocal spherical mirrors of different curvature, in the mutual focal plane of which a ring exit mirror with the coupling hole is located. Due to a high degree of diskrimination of higher-order modes with respect to losses, the lowest-order mode is surely selected in the resonator. In [8], the modulation unit assembled with the help of spherical mirrors and a rotating disk, as well as the spherical mirror of the resonator are located outside the laser. Stable repetitively pulsed lasing with the mean power up to 3 kW is obtained.

The goal of the present work is to investigate a new method of getting repetitively pulsed regime of oscillation in a CO_2 laser with a self-filtering resonator, based on the use of two equal-curvature cylindrical mirrors in the intracavity modulator. This allowed reduction of the *Q*-switching time, or the time of opening the shutter to pass the beam, and a high-power leading peak in the pulse of radiation at the mean power up to 5 kW was obtained without any effect of the radiation on the modulator aperture. The prospects of using the created radiation source for igniting the POD in a supersonic air flow are demonstrated. For the first time a detailed study of the mechanisms of energy absorption in flows at Mach numbers M = 1.7 – 3.7 is carried out, and the absorption coefficients versus the air density and velocity are measured.

2. Experimental setup

The repetitively pulsed CO_2 laser with mechanical *Q*-switching was built on the basis of a cw CO_2 laser with convective cooling of the active medium [13]. The self-filtering unstable resonator (Fig. 1) formed by the spherical mirrors SM1 and SM2 and the output mirror OM was used. The plane folding mirrors FM1 and FM2 in Fig. 1 schematically indicate the fact

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that in the laser a multi-pass cavity (eight passes) with the total length of 12 m is used. In this case, efficient CO_2-laser energy extraction is provided, the active medium having the dimensions $100 \times 6 \times 10$cm (a 'two-storied' excitation scheme is used with the separation between the electrodes 8 cm, the length of the active medium 100 cm and its size along the flow ~10 cm). The self-filtering unstable resonator has a feedback arm with the length $f_2 = f_{21} + f_{22} + f_{23}$ (Fig. 1). In this arm, the length of which in the present case is equal to 2 m, the beam has the diameter K times smaller than in the amplifying arm having the length $f_1 = f_{11} + f_{12} + f_{13}$ ($K = f_1/f_2 = 4.25$ being the magnification coefficient of the resonator). The power of radiation in the feedback arm is about $K^2/2 - 1$ times smaller than that in the output beam. Figure 1 schematically shows that a part of the radiation beam path in the feedback arm is passing through the active medium. The small beam diameter and the smaller power in the feedback arm make it convenient to mount here the elements of control of the radiation characteristics, in particular, the Q-switch. The latter was chosen to be a mechanical modulator (a rotating disk with slits) [9].

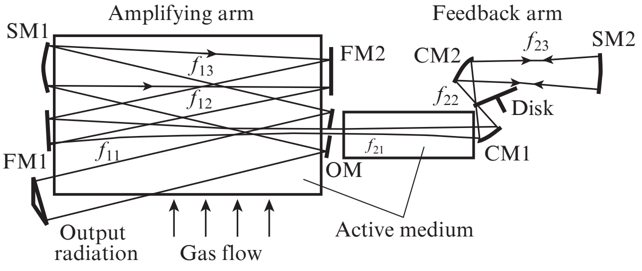

Figure 1. Schematic of the self-filtering resonator with the intracavity cylindrical telescope and the modulator disk:
(SM1, SM2, OM, FM1, FM2) mirrors of a multipass resonator; (CM1, CM2) mirrors of the cylindrical telescope; f_{13} is the separation between the centres of the mirrors SM1 and FM2; f_{12} – between the centres of the mirrors FM1 and FM2; f_{11} – between the centres of the mirrors FM1 and OM; f_{23} – between the centres of the mirrors CM2 and SM2; f_{22} – between the centres of the mirrors CM1 and CM2; f_{21} – between the centres of the mirrors OM and CM1.

To obtain a high-power leading peak in the pulse, one has to reduce the time of Q-switching, or the opening time of the shutter. To reduce the beam dimension in the feedback arm at the location of the disk, a telescope is used, consisting of two cylindrical mirrors CM1 and CM2 with equal curvatures. The telescope parameters were chosen such that after a double pass through the telescope the introduced distortions of the field distribution in the beam were negligibly small.

For filtering the beam the filtering diaphragm should be placed in the focus of the small spherical mirror M2 of the resonator, i.e., the condition $L_{eq} = f_2$ should be satisfied, where L_{eq} is the equivalent length of the smaller arm, and f_2 is the focal length of the smaller spherical mirror. In the presence of the telescope in the smaller arm the equivalent length has different values in the tangential (in the direction along the beam and parallel to the element of cylinder) and sagittal (in the direction along the beam and perpendicular to the element of cylinder) planes. The beam in the sagittal plane is focused and in the tangential plane it is not focused: $L_{eq} = L$ in the tangential plane and $L_{eq} = L - 2f$ in the sagittal one. Here L is the physical length of the smaller arm and f is the focal length of the telescope cylindrical mirror. The effective length being different, the conditions of filtration and the beam quality will be also different for different planes. To reduce this difference and optimise the filtration conditions one should choose the length of the smaller arm equal to $L - f$ and the distance f should be as small as possible. However, with the decrease of f the sensitivity of the telescope to the precision of tuning becomes higher. Keeping in mind the conditions under which the width of the beam waist in the focus of the cylindrical telescope is minimal, f should be taken equal to some optimal value, determined by the balance between the diffraction and the geometric aberrations.

Therefore, the intracavity telescope must satisfy the following conditions: the small dimension of the beam waist in the sagittal plane; the minimal difference of optical lengths of the smaller arm of the resonator for tangential and sagittal planes; the minimal phase distortions of the beam passing through the resonator in the forward and backward directions; the acceptable sensitivity to the variations of the parameters, i.e., the angles of incidence and the separation between the telescope mirrors.

Optimisation of the telescope was implemented using the ZEMAX program for calculating optical systems. From the calculations it follows that in the focal plane of the telescope an extensive waist is formed having the length 8 mm (the diameter of the unfocused beam) and the transverse dimension which is determined by the curvature radii of the telescope mirrors and amounts to ~200 μm. The focal length f of the cylindrical telescope mirrors is chosen to be 50 mm. In this case the relative variation of the equivalent length of the smaller arm amounts to ~0.03, which does not cause significant difference between the laser beam quality in the tangential and sagittal planes.

To reduce the resonator losses and to provide the installation technological effectiveness, the modulation units are installed inside the laser module. The exterior view of the modulation unit is shown in Fig. 2. The modulator disk, the high-speed drive and the positioners are seen. A specific feature of the proposed design is that the modulation unit is for the first time placed inside the active laser volume, and the whole setup can be considered as a high-power technological repetitively pulsed laser.

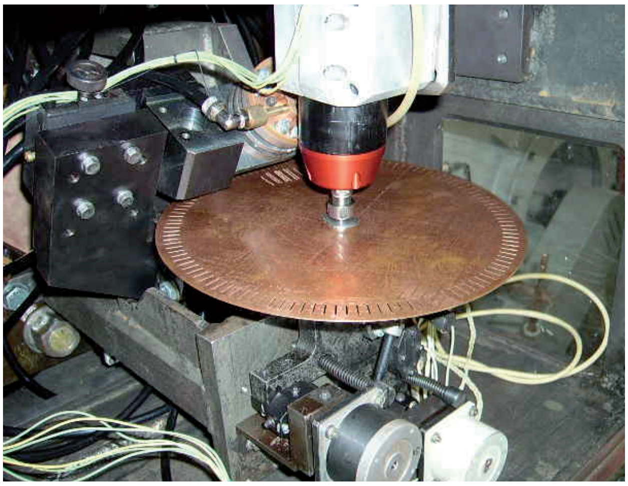

Figure 2. External view of the modulation unit.

3. Investigation of energy and temporal characteristics of the laser

Formation of the oscillation pulse begins at switching on the Q factor of the resonator. During the time between the oscillation pulses, when the disk blocks the resonator axis and the pump current continues to flow through the active medium, the processes that occur include the excitation of the upper laser energy level, the spontaneous relaxation of the lower laser energy level and the accumulation of the electric discharge energy in the laser transition. When the resonator axis is open, the radiation pulse begins to form. The population inversion in this case significantly exceeds the stationary value. The experiments were carried out in the CO_2 laser with convective cooling of the gas and transverse discharge pumping [13]. The gas flow velocity ~50 m s^{-1} was directed perpendicular to the discharge axis. The characteristic size of the discharge region in the direction of the flow was equal to ~100 mm. At the typical repetition rate of 50 kHz during the time between the adjacent pulses (20 μs) the gas flow passed ~1 mm, so that different parts of the medium, taking part in the formation of the radiation pulse, appeared to be at different stages of excitation (the scheme of the laser resonator was a multi-pass one, see Fig. 1).

The mean output power of the laser was measured with a standard NOVA 2 calorimetric meter having the limit measured power up to 5 kW. A FSG22-3A1 photodiode was used to monitor the time dependence of the radiation, incident on the plasma and passed through it. Using a FEK 22 vacuum phototube the glow intensity from the optical breakdown plasma was measured.

The oscillograms of the oscillation pulse (Fig. 3) have a characteristic front peak and a quasi-stationary plateau. The calculation of the pulse power was carried out as follows. First, the energy in a single pulse was determined by division of the mean power by the repetition rate. In further calculations the method of numerical integration of the oscillogram was used. From Fig. 3 it follows that the pulse power reaches ~200 kW at the half-width peak duration not greater than 500 ns. The total radiation pulse duration in the quasi-stationary phase (plateau) with the power, nearly equal to twice the cw power (mean power 4.5 kW), is not less than 5 μs.

The Q-switching system allows wide-range variation of the pulse repetition rate and the off-duty ratio, as well as the shape of the oscillation pulse, at the expense of the variation of the angular velocity of the disk rotation, the slit width, the number of slits, and the composition of the working gas mixture. In the work the disks with 40, 120, 300, and 400 slits were used, which allowed the maximal pulse repetition rate up to 80 kHz at the disk rotation rate 180 Hz.

Figure 4 plots the dependences of the mean oscillation power and the efficiency in the cw and repetitively pulsed regimes on the discharge power in the developed laser. The increase in the modulation frequency leads to the mean power in the repetitively pulsed regime asymptotically approaching the cw power. For the maximal frequency at which the experiments were carried out (80 kHz) the power difference was ~0.8 kW and the efficiency difference was about 1%. The results of the study of the mean and the pulse power of laser generation depending on the pulse repetition rate are presented in Fig. 5. It is seen that the mean power increases with frequency. However, while for the high-power energy action

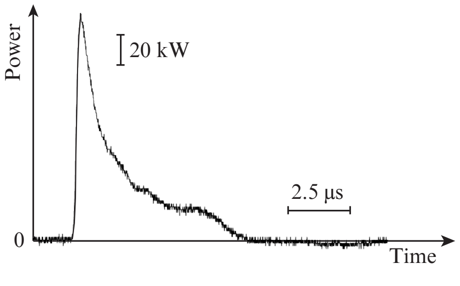

Figure 3. Oscillogram of the laser pulse. The modulator disk had 120 1-mm-wide slits. The mixture is CO_2 : air = 1 : 5. The pulse repetition rate is 54 kHz.

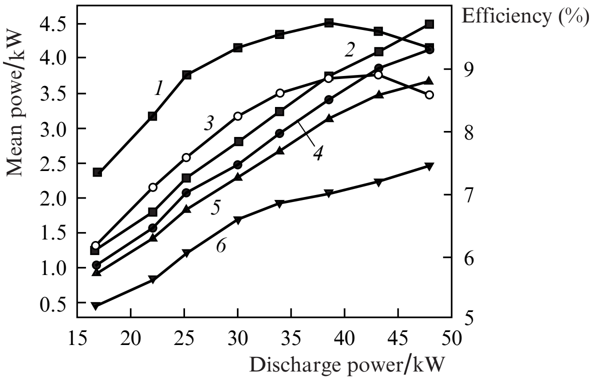

Figure 4. Dependences of the efficiency (*1*, *3*) and mean output power (*2*, *4*–*6*) in the cw (*1*, *2*) and repetitively pulsed (*3*–*6*) regimes on the discharge power for the mixture CO_2 : air : He = 1 : 7 : 8. The pulse repetition rate 54 (*3*, *4*), 21 (*5*), and 7.2 kHz (*6*).

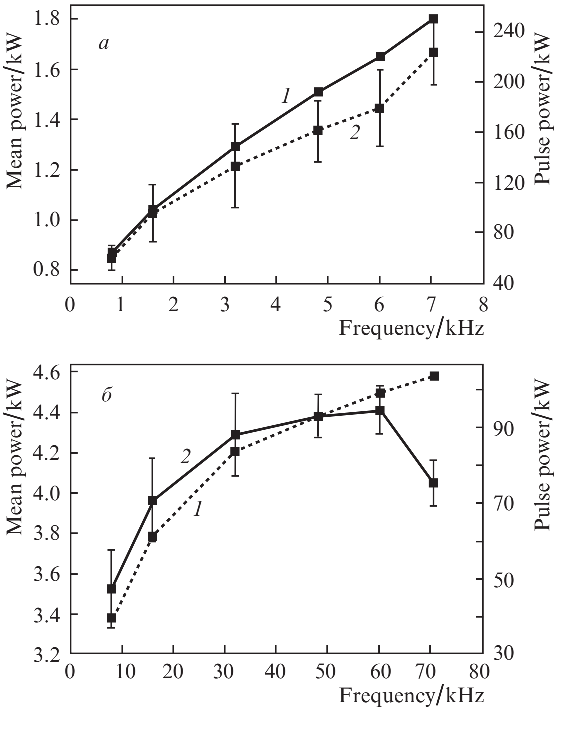

Figure 5. Dependences of the mean (*1*) and pulse (*2*) power of the laser on the pulse repetition rate for the mixture CO_2 : air : He = 1 : 7 : 8. The modulator disk had 40 slits 1 mm wide (a) and 400 slits 0.5 mm wide (b).

on a supersonic air flow the mean power is of primary importance, the discharge ignition is principally dependent on the rate of rise and the peak value of the instantaneous pulse power [14]. Experiments have shown that the minimal duration of the leading edge of the pulse is achieved under the maximal angular velocity of the disk rotation and is practically independent of the number of slits. The duration of the leading edge varies from 130 ns at the disk rotation rate 180 Hz to 240 ns at the disk rotation rate 20 Hz. However, in Fig. 5a one can see that there is an optimal pulse repetition rate, corresponding to the maximal peak power.

Thus, for highly efficient ignition of the discharge, i.e., for obtaining the maximal mean and peak power at minimal duration of the leading edge of the pulse, it is necessary to use the optimal regime of laser operation with the pulse repetition rate ~40 kHz, maximal rate of disk rotation ~180 Hz and the number of slits 200–300.

4. Study of the optical breakdown in supersonic air flows

The studies of the optical discharge were performed using two setups. For investigating the averaged structure and characteristics of a supersonic flow in the presence of an optical spark a low-sized wind tunnel was used that provided a uniform air flow in the range of Mach numbers from 2 to 7. A quick-acting valve provided pulsed outflow of compressed air, accumulated in gas vessels, into the gas-dynamical tract of the setup. At starting the setup operation a quasi-stationary supersonic flow is provided during ~1.5 s at the exit of the shaped nozzle with the diameter 100 mm [9].

To study the energy absorption mechanisms in the gas, the second setup was used, in which a supersonic gas flow propagating in free space was produced (Fig. 6). In the photograph one can see a ball-shaped glow of the optical discharge plasma and a thermal trace. The setup comprised a supply pipe-line with the diameter 15 mm connected by means of a flexible hose with the settling chamber and the conical nozzle. The total pressure of the flow was measured in the settling chamber. The experiments were carried out at the maximal pressure 1.8 MPa in the settling chamber. For the conical nozzle with the aperture angle 13° and the exit section diameter 10 mm, the diameter of the critical section being 8 mm, the geometrical Mach number was 1.9. In this case the gas consumption was 2–4 kg s^{-1}.

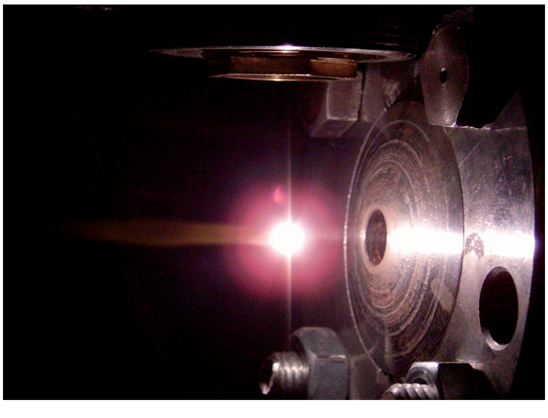

Figure 6. External view of the setup for studying supersonic gas flow, propagating in a free space.

To observe visually the plasma formation process in a supersonic flow and the thermal trace, produced by the plasma, the setup was equipped with a system of optical diagnostics. The system comprises the optical attachment to shadow devices on the base of adaptive visualising transparencies, developed at the Institute of Theoretical and Applied Mechanics, Siberian Branch of the RAS [15] as a unit with the collimator based on TAL-100R telescopes and a high-speed video camera with the exposure time ~1 ms. A cw diode-pumped laser at the wavelength 532 nm was used as a source of probing radiation.

After passing through the ZnSe lens with the focal length 63 mm, the laser radiation was incident on the axis of the supersonic jet perpendicular to the gas flow. The diameter of radiation spot in the lens focus was 100–150 μm, which in the optimal laser operation regime provided the peak intensity (7–15) × 10^8 W cm^{-2}. After passing through the jet and the zone of plasma production the laser radiation was absorbed by the NOVA 2 calorimetric power meter with the limit measured power 5 kW.

Figure 7 presents a shadow photograph of the optical discharge in the supersonic flow at the Mach number $M = 2.0$, the pulse repetition rate 54 kHz, and the mean power of laser radiation 3.2 kW. In front of the region of the optical discharge a bow shock wave is formed, similar to that in front of an obtuse solid body. The plasmoid is followed by a thermal trace whose configuration varies downstream. The maximal transverse dimension of the plasmoid amounts to 5–6 mm. It is important to note that each frame is a result of averaging over ~20 pulses (the time interval between the pulses being 20 μs). Therefore, in spite of the periodical character of energy supply and the high rate of plasma recombination in air, a quasi-stationary structure of the gas flow is observed.

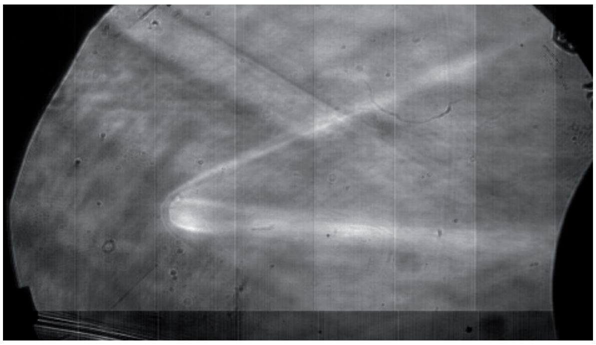

Figure 7. Shadow photograph of the optical discharge in the supersonic flow.

The coefficient of radiation absorption inside the plasmoid is of primary importance for using the quasi-continuous optical discharge as a means of distant introduction of energy into the air flows, including supersonic ones. The measurement of the energy absorbed in the supersonic flow was performed at the discharge ignition in the free air jet.

Absorption of CO_2 laser radiation in the plasma of the optical discharge may be evaluated using the complex dielectric permittivity $\varepsilon' = \varepsilon + i\sigma$, where

$$\varepsilon(\omega) = 1 + \frac{\omega_p^2(\omega_0^2 - \omega^2)}{(\omega_0^2 - \omega^2)^2 + \nu^2\omega^2}; \quad \sigma(\omega) = \frac{\omega_p^2 \nu\omega}{(\omega_0^2 - \omega^2)^2 + \nu^2\omega^2};$$

$\omega_p^2 = 4\pi e^2 N_e/m$ is the square of the plasma frequency, ω_0 is the resonance frequency, ν is the rate of collisions between the electrons and particles. For free electrons ($\omega_0 = 0$ and $\omega \gg \nu$) we get $\varepsilon(\omega) = 1 - \omega_p^2/\omega^2$ and $\sigma(\omega) = \omega_p^2 \nu\omega/\omega_0^4 = 4\pi e^2 N_e \nu\omega/(m\omega_0^4)$, i.e., the absorption increases with the growth of the electron concentration N_e. However, the radiation penetrates into the plasma under the condition $\omega_p^2/\omega^2 \leqslant 1$. Therefore, at a given frequency ω of radiation its penetration into the plasma is limited by the condition $4\pi e^2 N_e/(m\omega^2) \approx 1$. For the CO_2 laser (λ = 10.6 μm) the critical value of N_e is equal to $\sim 10^{19}$ cm^{-3}. According to the data of Ref. [14], the necessary parameters of the plasma with the concentration of electrons $N_e \sim 10^{19}$ cm$_{-3}$ in still air may be obtained at the power density 5×10^8 Wcm^{-2} and the concentration of molecules $\sim 3 \times 10^{19}$ cm^{-3}. Such values of N_e imply operation at atmospheric and higher gas pressures, since at pressures lower than the atmospheric one it is difficult to provide a near-100% degree of ionisation in the plasma of the optical discharge.

A shadow photograph of the flow at the pressure 1.5 MPa in the settling chamber in the absence of plasma is presented in Fig. 8a. The flow structure in the presence of the optical breakdown is shown in Fig. 8b. The measurements of the absorption coefficient were performed within the limits of the so-called first barrel of the supersonic jet along its axis at different distances from the nozzle exit section. In this case the processes of interaction of laser radiation with the supersonic flow are identical with those in the low-sized aerodynamic setup.

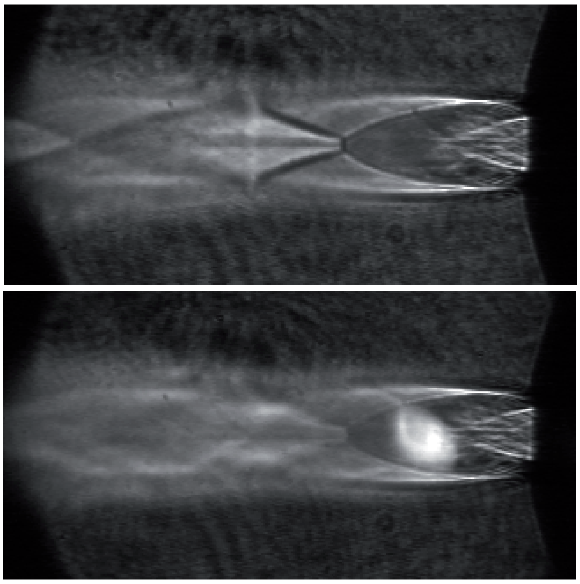

Figure 8. Shadow photographs of the supersonic flow in the absence of plasma (a) and the flow structures at the optical breakdown (b). The pressure in the settling chamber is 1.5 MPa.

Figure 9 presents the oscillograms of the incident and transmitted pulses of laser radiation and the plasma glow in the supersonic air flow. It is seen that at the front of the high-power laser pulse during the first 50–70 ns from its beginning the gas breakdown occurs and the plasma glow appears. This is accompanied with efficient absorption of laser radiation causing significant decrease in its intensity. It is interesting that the time dependence of the integral intensity of the plasma spark glow is nonmonotonic, i.e., has two maxima, which are apparently caused by the spark dynamics and the variation of conditions of light propagation (optical clearing of the plasma).

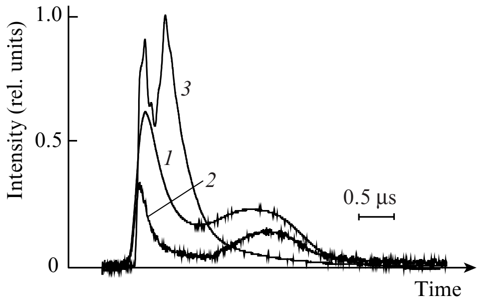

Figure 9. Oscillograms of the pulses of the incident (*1*) and transmitted (*2*) laser radiation and the plasma glow in the supersonic air flow (*3*).

The parameters of the flow streaming into the surrounding atmosphere were determined by solving the Navier–Stokes equations numerically with the help of the FLUENT software package. The numerical modeling possibilities and the comparison of its results with those of experiment were thoroughly diskussed in the literature (see, e.g., [16]). The calculations were carried out for a number of values of the pressure in the settling chamber p (0.8, 1.15, and 1.5 MPa) and the corresponding regimes of underexpansion. The flow parameters at intermediate pressures were determined using interpolation of the calculated data.

Table 1 presents the calculated values of the density ρ, Mach number M and the velocity V along the axis of the air flow at different distances x from the nozzle exit section, as well as the absorption coefficients Π of the laser radiation, measured in different points on the jet axis.

In Fig. 10 the data of Table 1 are presented as a plot of the absorption coefficient versus the gas density. They allow one to conclude that a range of gas densities, or, to be more precise, a certain minimal air density exists, after attaining which

Table 1.

ρ/kg m^{-3}	M	V/m s^{-1}	Π(%)	x/mm	p/MPa
4.95	1.85	486	43.8	3	1.5
4.72	1.92	497	55.6	3.5	
4.18	1.99	508	59.8	5	
3.62	2.12	532	57.7	7	
3.17	2.24	540	54.6	9	
2.77	2.36	555	45.1	11	
2.1	2.61	580	17	13	
1.43	2.96	609	13.8	15	
0.66	3.71	654	11.7	20	
3.47	1.95	502	55	4.5	1.15
3.1	2.05	516	55.3	6	
2.87	2.12	525	56.7	7	
2.7	2.18	533	48.3	8	
2.05	2.42	561	13.8	12	
2.7	1.85	487	47.7	3	0.8
2.5	1.92	497	45.5	4	
2.31	1.99	507	47.1	5	
2.16	2.05	516	46.1	6	
2	2.12	525	46.8	7	
1.87	2.18	533	49	8	
1.75	2.24	540	41.4	9	
1.63	2.3	547	29.1	10	
1.53	2.36	554	21.8	11	

one can observe efficient absorption of the laser energy in the plasma of the optical breakdown in the supersonic air flow. In our case this density amounts to 1.8 – 2 kg m^{-3} (the concentration being 10^{19} cm^{-3}), which is in good agreement with the estimates presented above. It is important to note that the critical density does not depend on the regime of the flow formation at the pressures 0.8 – 1.5 MPa in the settling chamber. In spite of the high gas velocity (500 – 650 m s^{-1}) and high Mach numbers (1.8 – 3.7) one can see that in the whole range of the measure quantities the efficiency of the energy absorption is mainly determined by the air density. In other words, at the given mean power and the wavelength of the radiation, the minimal density of the supersonic air flow exists, at which the maximal absorption of the energy in the plasma of the optical breakdown is observed.

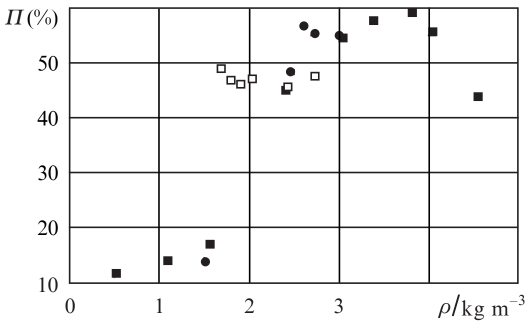

Figure 10. Dependences of the absorption coefficient Π on the gas density ρ for the chamber pressures 1.5 (■), 1.15 (●), and 0.8 MPa (□).

5. Conclusion

We present the results of the study of the new-built high-power repetitively pulsed CO$_2$ laser with mechanical Q-switching. The laser pulse power more than 200 kW and the mean power up to 5 kW are achieved.

The possibility of efficient optical breakdown and the POD ignition in a supersonic wide-aperture air flow in a wide range of gas-dynamical characteristics is demonstrated.

For the first time it is found that the threshold air density in the supersonic flow, corresponding to the sharp increase in the absorption efficiency, is equal to 1.8 – 2 kg m^{-3}.

For the first time the absorption coefficient of laser radiation in the plasma of the optical breakdown is measured in the supersonic air flow within a wide range of gas dynamical parameters. The maximal absorption coefficient amounts to 60 %.

The results of our studies allow determination of the supersonic flow parameters providing high heat input and, therefore, the possibility to control the structure of such a flow.

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