Laser breakdown model in the absorption mode behind a light supported detonation wave

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Abstract. The light supported detonation wave (LSDW) propagation with the laser radiation absorption in a narrow layer behind wave's front is considered in the paper alternatively to the volumetric energy source model usually used for the energy deposition simulation [1-7]. The next laser plasma flow features were revealed in [8] by methods of numerical simulation:
1) laser plasma forms high-speed jet flow behind the LSDW front along the light beam propagation direction,
2) jet parameters are close to an isentropic flow mode at significant distances from the LSDW front, therefore can be determined with a good approximation using the unsteady pressure solution for the point explosion model with a kinematic x-t transformation.

These features allow one to determine the plasma momentum value (in the direction of a laser beam) of the optical breakdown as an additional factor of effect on gas flow, first indicated in [9].

For an argon flow, we used a comparative analysis of the results of numerical simulations obtained both accounting the absorbed energy only and the breakdown plasma momentum additionally acquired at the absorption of radiation behind the LSDW front.

The experimental results of an optical discharge plasma in a subsonic argon flow are presented. Pulse-periodic radiation with a frequency of 40 kHz and average power of 1.6 kW (peak power more than 30 kW) was generated by CO2-laser created in ITAM SB RAS. In order to obtain the LSDW mode by increasing a length of the breakdown plasma a focusing system f / d ≈ 9 was applied. A high-speed video camera with the exposure time of 1.0 μs, and the shooting speed of 200,000 frames / sec was used to record process. It has been established that the plasma dynamics has two successive stages: from the initial high-speed (of the order of 1 μs) propagation of the optical discharge to the subsequent lower-velocity gas-dynamic stage.

Analytical model. A general approach for simulation of a laser energy deposition in the radiation absorption mode behind the front of LSDW is to assume that the energy and momentum of the breakdown plasma are “instantaneous” with respect to the characteristic time scales of gas-dynamic processes. Such a breakdown mode is possible at a sufficiently long beam focusing, i.e. when the length of the caustic beam is significantly larger than its diameter.

Within the framework of the model used, the condition of “instantaneous” increase of the directional plasma velocity is also valid due to the short duration of the radiation pulse and the high velocity of the LSDW front (~ 1 μm, V ~ 10 km/s) relative to the characteristic scales of gas-dynamic processes. The front moves towards the beam with the velocity determined by the relation \( V = \left[2(\gamma^2 - 1)J/\rho_\infty\right]^{1/3} \), where \( J \) is the average of the radiation power density [W/m²], \( \rho_\infty \) [kg/m³] – free flow gas density, \( \gamma \) is the effective value of the ratio of specific heat capacities that is \( \gamma \approx 1.2 \pm 0.05 \) in the characteristic breakdown regime of a strongly ionized plasma. Beam of diameter \( d \) has power density that can be estimated by the value \( J = N/(\pi d^2/4) \), where \( N \) is the absorbed power.

Plasma momentum value of the laser breakdown in the direction of propagation of the laser beam can be estimated by the relation: \( P = (1/x_0)|\rho(x)u(x)|r(x)/r_0|^2 \)dx, where the axial distributions of parameters are
use: density $\rho(x)$, flow velocity $u(x)$, radius of the contact surface $r(x)$. Introduction of the factor $\left[\frac{r(x)}{r_0}\right]^2$ takes into account the increase of the jet cross-sectional area with the distance from the front. Parameter $r_0$ is the caustic radius and, accordingly, the radius of the LSDW front. Integration limits are $x = 0 \rightarrow x_0$, where $x_0 = V\tau$ is the distance that the LSDW front passes during the pulse of radiation $\tau$, i.e. the extent of the plasma.

Such flow parameters as enthalpy, density, and velocity along the axis correspond to an isentropic flow with an accuracy of no more than 10% at a sufficient distance from the wave front, as was resulted in [8]. Therefore, the degree of pressure decrease allows parameters determination in the axisymmetric flow. In addition, the radial density distribution is approximately uniform up to its contact surface that allows one to determine the radius of the jet from the continuity equation for the entire flow as a whole.

Thus, the flow pressure $p(t)$ is the key parameter necessary for definition of the jet parameters. For this purpose, as it has been done in [8], non-stationary solutions obtained in the framework of the model of a point cylindrical explosion are used for definition of the shock wave radius $r(t)$ (the contact surface behind the front of the LSDW) and the pressure $p(t)$ behind front [10]:

$$r(t) = \left(\frac{E_0}{\rho_0}\right)^{1/4} t^{1/2}, \quad p_2 = \frac{2}{(y+1)} \rho \left(\frac{dr}{dt}\right)^2 = \frac{\rho}{2(y+1)} \left(\frac{E_0}{\rho_0}\right)^{1/2} t^{-1}$$  (1)

In this model, the dimensionless parameter $\alpha = \frac{E_0}{E}$ determines the relationship between the energy parameter $E$ and the amount of energy $E_0$ allocated per unit length, so that $E_0 = \alpha E$; the parameter depends on the properties of the gas and increases with decreasing $\gamma$. In accordance with the data of [10], $\alpha = 2$ at $\gamma = 1.2$, and when $\gamma$ is varied within the range of $\gamma = 1.2 \pm 0.05$, the parameter changes significantly, $\alpha \approx 2.5$ ($\gamma = 1.15$) and $\alpha \approx 1.5$ ($\gamma = 1.25$).

In the central region of the explosion the magnitude of the pressure $p$ stabilizes for a short time and accounts for a certain proportion of the pressure $\beta$ at the shock wave, i.e. $p = \beta p_2$. Moreover, the degree of pressure decreasing depends on the properties of the gas, and, for example, $\beta = 0.442$, 0.426, and 0.441 at $\gamma = 1.15, 1.2$, and 1.25, i.e. this coefficient is much weaker than $\alpha$ depends on the properties of the medium.

Kinematic transformation $x = Vt$ is used firstly to determine the axial pressure distribution $p(x)$ in the flow behind the LSDW front from equations (1). That is valid for the areas far enough from the point "explosion". In the paper [8] mentioned above it has been shown that the numerical and analytical solutions converge even at $x/d \geq 4$. In this case, using the expressions (1) and for the velocity of the LSDW, as well as the relationship between the energy parameters of laser radiation and cylindrical explosion, $E_0 = N/V = \frac{\pi d^2}{4} V$ one can get:

$$\left(\frac{E_0}{\rho_0}\right)^{1/2} = \left[\frac{\pi}{8\alpha(y^2-1)}\right]^{1/2} V d$$  (2)

As a result, it is possible to determine the axial pressure distribution that takes the following form:

$$p(x)/\rho_\infty V^2 = K_p (x/d)^{-1}, \quad K_p = \left[\frac{\beta}{2(y+1)}\right] \left[\frac{8\alpha(y^2-1)}{\pi}\right]^{-1/2}$$  (3)

Then, other parameters of the jet flow behind the LSDW front can be determined from the equations of isentropic flow resulting in the relative magnitude of the plasma momentum $P/P_0$ ($P_0 = \rho_\infty V$).

This parameter dependence on the relative distance $z = x/d$ is shown in Figure 1. The range of values of the specific heat capacity ratio is $\gamma = 1.15 \rightarrow 1.25$. It is characteristic range for the breakdown plasma that

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**Figure 1.** Plasma momentum depending on its length $z$. $P_0 = \rho_\infty V$. 

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was used taking into account the corresponding changes in the values of the coefficients $\alpha(\gamma)$ and $\beta(\gamma)$ in the theory of a strong cylindrical explosion. We should note that near the front ($z = 0–0.25$), due to the strong violation of the monotonic change in the approximate solutions, we used their linear approximation to values corresponding to the parameters at the detonation wave front. The sought parameter is negative in the region $z < 1$ where flow velocity is lower than the velocity of the LSDW front ($u/V < 1$). However, because this region is small and its contribution to the momentum acquired by the plasma is insignificant, the effect is completely determined by the flow parameters at large relative distances. This parameter grows intensely at small $z$, slightly increasing at $z > 15$–20 to values in the range of $P/P_0 \approx 0.2–0.3$; for this reason, it is not reasonable to increase the length of the breakdown plasma significantly.

The breakdown plasma momentum depends rather weakly on the ratio of the specific heats of the plasma. In the characteristic range of changes of $\gamma = 1.15–1.25$, the relative change in momentum is of 12–14% at $z = 15–40$. However, the real value of this parameter also depends on the degree of fulfillment of the assumptions used in this model: a uniform distribution of the power density over the beam cross section and the “step” shape of the radiation pulse in time. Stationary solutions for isentropic flow one can use only at a sufficiently large elongation of breakdown plasma ($z > 1$). In addition, radiation losses can affect the plasma jet parameters. However, the ratio the integral plasma radiation flux over the spectrum to the flux of laser radiation power is less than 0.08 that allows us to neglect the influence of radiative losses when evaluating the parameters of the breakdown plasma behind the LSDW front. Analogous conclusion was obtained in [11] for similar conditions.

In conclusion, we note that in this model, the magnitude of the breakdown plasma momentum depends on the focusing conditions, taking into account a certain relationship between the parameters: $V \propto J^{0.3}$ and $J \propto d^2$. The proposed method for estimating this parameter is universal due to the absence of dependence of the flow parameters on the beam diameter and its power in explicit form. Despite the indicated limitations, the general form of the dependence of the plasma pulse $P \propto P_0$ is retained but with some correction accounting for the real conditions of laser breakdown.

Therefore, the presented relatively simple method of accounting the LSDW-regime allows one to determine the characteristic effects in the flow structure within the framework of the developed numerical methods. The numerical simulation data presented below demonstrate certain changes of subsonic gas flow structure. In addition, the results of experiments with an optical discharge at close conditions show the need of monitoring the dynamics of the laser radiation power absorbed by the plasma.

**Numerical simulation results.** Numerical simulation of laser energy deposition to a subsonic argon flow has been carried out using the academic version of the ANSYS FLUENT software package for an unsteady problem in an axisymmetric formulation. Computational domain is covered by mesh with $\sim 0.6 \text{mln}$ regular cells. It includes a subdomain located on the axis and elongated in the flow direction. This subdomain contains energy sources and forces defined using functions written in C language (‘user defined functions’).

The energy source for the momentum conservation equation defined as the specific absorbed power of the laser pulse [W/m3] as well as the calculated values of the plasma specific momentum $P/\tau = 0.2 \rho_0 V/\tau$ [N/m3] were used for numerical simulation. The length of the breakdown region $l$ is in accordance with the condition $l = u/\nu$, where $u$ is the velocity of the free flow, $\nu$ is the frequency of the laser pulses. This condition means that during the time interval between pulses $1/\nu$, flow shifts the breakdown plasma at the distance equal to its length.

Euler equations were solved within the framework of the used software package. We used the ‘density-based’ FLUENT solver, an implicit Roe second-order approximation scheme. At the external boundary of the computational domain ‘pressure-far-field’ type of conditions is used. A condition of type ‘pressure-outlet’ is set at the output boundary. ‘Axis’ type of condition is specified on the boundary that is axis.

The perfect gas equation is used; the heat capacity is assumed to be constant. Viscosity is described by Sutherland’s law.

To eliminate the possible influence of boundaries introducing disturbances into the solutions, expanded, almost square region, with dimensions up to 100 lengths of the energy / momentum source is considered.

Figure 2 shows the results of the calculation of the axial density distributions. Figure 3 presents results of the axial distribution of the flow velocity behind the breakdown region in the argon subsonic flow. Both Figures show results obtained at simulation with accounting only energy deposition of the break-
down plasma (a) and supply into the flow both the energy and momentum P (b). One can see the time moment after the fourth breakdown. The conditions in the flow correspond to the subsonic (M = 0.67) isobaric (1 atm.) argon flow when it expands with the initial parameters: 1.4 atm. and T = 290 K. The length of the breakdown plasma is of $l = 4$ mm.

Follows peculiarities of the wave structure can be observed when both the energy and momentum of the plasma are taken into account at the numerical simulation.

1. Local supersonic flow regions appear during the “switch on” of the radiation source (i.e., energy-momentum sources) with the initial stage of the shock waves formation and their destruction in times between pulses.

2. Immediately after the end of the radiation pulse, zones with high velocity appear not only in the axial but also in the radial direction that leads to increasing the radius of the density disturbance region.

3. Not as significant as it is when energy and momentum sources are deposited into a supersonic flow [9], but nevertheless, the thermal wake length increases.

![Figure 2. Density distribution in the subsonic argon flow, energy supply x \approx 0.15–0.155 m. Range of variation 0.10 – 5.35 kg / m$^3$ (left); 0.20 – 3.40 kg / m$^3$ (right, accounting the plasma pulse).](image)

Moreover, the axial velocity is increasing sharply during energy deposition. The velocity becomes equal to the velocity of the external flow at distances of about the length (0.005 m) of the energy deposition region. In this case, the radial distribution of this parameter has a peak with a radius of \( \sim 0.0015 \) m, followed by the disturbance level decreasing.

![Figure 3. Axial velocity distribution in subsonic argon flow. Range of variation -510 – +685 m / s (left); -1500 – +3000 m / s (right, accounting the plasma pulse).](image)

Thus, data shows that in subsonic flow, the structure formed is substantially more non-uniform accounting for both energy and plasma momentum due to amplification of the unsteady disturbances in all directions in comparison with the data for energy supply only. The amplification effect is due to interaction between high-speed micro-jet and gas flow.

**Experimental results.** In experiments, the radiation of a CO2 laser was used [12], working in a pulse-periodic mode, with an average radiation power of 1.5–2 kW, and a laser pulse frequency of 40 kHz. A Zn-Se lens with focal length of 254 mm was used to form an extended caustic (up to 3 mm, diameter 150
μm) of the laser beam with diameter of $D = 27-30$ mm. A Zn-Se lens with focal length of 254 mm was used to form an elongated caustic (up to 3 mm, diameter 150 μm) of the laser beam with diameter of $D = 27-30$ mm. This condition ($f/D \approx 9$) allowed obtaining extended breakdown plasma in the LSDW mode.

The argon flow was created in the slotted channel with a cross section of 10 (direction of observation) × 3.7 mm²; overpressure at the inlet is in the range of 0.5-0.8 atm. Plasma displacement was up to 5 mm at the pulse frequency of 40 kHz in the subsonic flow with the velocity up to 200 m/s. The breakdown process was recorded using the shadow and schlieren shooting methods by FASTCAM SA-Z camera (Type 480K), exposure time (1.0 μs), and shooting speed of 200,000 frames/s (interval is of 5 μs). Different degree of attenuation of the object’s luminescence (diaphragm and light filters) allowed expanding the capabilities of the method used.

Gas breakdown (Figure 4, left) occurs at a radiation focusing point at the distance of 5-6 mm from the edge of the slotted channel. At maximum attenuation, the plasma glow was recorded only on two consecutive frames, with an extremely short exposure time of 1 μs. If one of them has a bright glow then on the previous one the glow is completely absent, and on the next one, the very weak glow exists only at a distance near the focus point of the beam. An analysis of the sequence of images with their large (1000-2000) number, taking into account the mismatch of these intervals ± (1-1.3) μs, allowed us to establish the initial dynamics of the breakdown plasma even in the absence of synchronization of the breakdown processes and the opening of the camera electronic shutter.

Figure 4 shows the initial and final stages of the breakdown process, with the time interval between them of about 1 μs. This data points the formation a linear structure with length of up to 5 mm. At the end of the final phase, the discharge glow intensifies in contrast to expected. In order to determine the cause of the glow effect the dynamics of the laser pulse as well as plasma parameters estimation in the high-velocity mode of absorption behind the LSDW front has been used. Since LSDW mode is realized at the radiation power density of (1-2) 10⁸ W/cm² that corresponds to the test conditions.

Figure 5 shows an oscillogram of a laser radiation pulse. At an average power of 1.6 kW of pulse-periodic (40 kHz) radiation, the total pulse energy is of 40 mJ. The results of previous studies showed that the main absorption (up to 50-60%) occurs in the region of the laser pulse peak and the one is very weak in the “tail” of it.

Kinematic parameters of the LSDW front: the velocity and distance passed in the corresponding time intervals, showed the following result. At the peak of the pulse the velocity is of 8 km/ s and then decreases to 4.6 km/ s taking into account 50% absorption. The distance passed in the time interval 0-1 μs estimated to be 4-5 mm that is close to the observation results and exceeds the length of the beam caustic (about 3 mm). An increase in the caustic diameter (1.2 times) still weakly affects the velocity that decreases to 4.0–4.2 km/s. According to estimates, after the end of the pulse peak (1 μs), the LSDW front can pass at least another 4 mm that was not observed in the experiment. Moreover, in contrast to the expected decrease in luminescence, at the final stage of the breakdown, its amplification reveals in a localized region (1-1.5 mm).

Plasma glow depends on the dynamics of its parameters behind the LSDW front. Estimates in the framework of this model show main fraction of radiation (at least 90%) is concentrated in a narrow (no more than 1-2 beam caustic diameter) plasma layer behind the front. Consequently, when registering a process with a strong attenuation of glow, the brightness in a frame results by the narrow plasma layer in the process of the LSDW front propagation. The brightness level depends on both the radiation intensity and the front velocity. In the experiment, the velocity decreases by half, from 8 to 4 km/s, while the radia-
tution intensity of the plasma layer decreases much more, about 100 times. Therefore, the camera will detect the brightness decrease of the wake up to its disappearance as the LSDW moves towards the beam at the front velocity decreases. This suggests that the observed glow brightness increasing caused by the drastic decrease of the front velocity due to the disruption of the LSDW regime and the subsequent absorption of already less intense laser radiation in the regime of (a) a laser spark or (b) fast ionization wave. The LSDW regime is known exists provided the ratio of the mean free path of radiation to the beam diameter should be much less than unity. The evaluation results for the experimental conditions showed that this criterion is not satisfied when the velocity of the LSDW is less than 4 km/s.

Level of the glow in a frame increases significantly at the recording using the diameter of the aperture increasing. Changing form of the recorded plasma glow region in the flow is shown in Figure 6 with the interval between frames (top to bottom) 5 μs. Figure 6, b in contrast to data presented in Figure 6 a, shows completely formed plasma at maximum elongation.

The gas breakdown occurs in one or in several close “points” (frames 1). Perhaps a multipoint breakdown is due to the presence of small particles in the flow. Then the glow patterns become identical. The plasma expands in the radial direction, stronger in the region of the initial breakdown (frames 2), followed by the formation of vortex-like structures (frames 3). Their general configuration and scale correlate with the data of numerical simulation taking into account the deposition of energy and momentum (Figure 2b, 3b).

![Image](image1)

*Figure 6. Glow of the plasma region, the interval between frames (top to bottom) 5 μs*

The following Figure 7 presents results of flow visualization obtained by the schlieren method. The time duration of the probe laser beam was 0.1–0.2 μs due to it switching on with a delay of 0.8–0.9 μs after opening the camera shutter (exposure time - 1.0 μs).

The short backlight time permitted to visualize the shock waves. In the early stages, shock waves with a characteristic scale of the order of 1 mm were registered. At the maximum plasma length, shock waves had shapes near to being an ellipse. In most of the images, the shock wave covers the entire discharge region, and its front is ahead of the plasma boundary. In some of the images, the plasma is adjacent to the upper edge of the channel caused by a small beam shift in this set of tests.

![Image](image2)

*Figure 7. Visualization of shock wave by the schlieren method.*

Estimates using the theory of point explosion for an energy parameter of 4 mJ / mm (cylindrical geometry, 20 mJ / 5 mm) show that in 4–5 μs after the explosion, the radius of the shock wave is of 3.5–4 mm that is on average close to that recorded
in the experiment. Estimated radius of the shock wave after 10 μs is of 5.5–6 mm, and, therefore, the shock wave is outside the frame. However, the characteristic radius of the luminescence region changes weakly and does not exceed 0.5–1 mm, which correlates with the estimate of the radius of low density (0.65 mm) obtained in the framework of the used model of point explosion accounting for backpressure.

**Conclusions.** Thus, the experimental results showed that the discharge plasma dynamics has two successive stages: from the initial high-velocity (of the order of 1 μs) propagation of an optical discharge with absorption of radiation behind the LSDW front to the next lower-velocity stage. At the initial stage, the discharge plasma has a line structure extending along the axis of the beam, in which, in accordance with the physical model, laser plasma forms micro-jet flow behind the LSDW front. At the next stage, the wave pattern in general manifestations, such as the characteristic scales of the shock wave and the region of high temperature and low density, correlates with representations within the framework of the instantaneous energy release model.

Detailed picture of the relationship of processes from the initial to subsequent stages one can obtain using complex approach using numerical simulation methods. In addition to the energy parameters, it is necessary to take into account the plasma flow momentum within the framework of the model of discharge propagation in the LSDW mode. With this approach, it is necessary first to take into account the real dynamics of the absorbed laser radiation, on which the velocity of LSDW front depends, respectively, the length and integral momentum value of the breakdown plasma.

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