Shock-wave processes evolution in fused quartz under intense energy action

V P Efremov, M F Ivanov, A D Kiverin and I S Yakovenko

Joint Institute for High Temperatures of the Russian Academy of Sciences, Izhorskaya 13
Bldg 2, Moscow 125412, Russia
E-mail: ivanov-mf@mail.ru

Abstract. The paper considers gas-dynamical processes evolving as a result of laser action in fused quartz. A conventional approach is used to construct a model for equation of state which provides an adequate description of the silica state at high densities of energy typical for local optical silica damage. Shock-wave processes generated in the medium due to the local laser energy deposition are calculated using fully conservative numerical technique. The obtained results provide relatively accurate description of the process in a wide range of parameters and allow further research to get clear interpretation of high-speed propagation of the laser absorbing front through the silica optical fiber.

1. Introduction

A principal difficulty in increase of the silica optical fibers bandwidth is the optical breakdown probability rise with laser power. Plasma discharges arise on the micro defects of the fiber glass producing the regions of high concentration of free electrons which in turn intensively absorb the laser radiation. As a result, a stable absorption front propagating towards the laser ray is formed. The temperature inside the absorption zone increases sharply that cause local destruction of the fiber. In the experimentally considered case [1] full energy absorbed by the medium is relatively low, not exceeding the amount of 0.25–0.6 mJ.

It should be noted that the focusing of the energy inside the optical fiber core of ~ 7.0–9.5 µm diameter causes rather high intensities reaching the value of 4.0 GW/cm² [1]. Such an energy concentration on the micro scales determines a specific physics of considered processes evolution and mechanisms of high-speed regimes of laser absorbing front and destruction wave propagation. At lower intensities of continuous laser radiation (of several MW/cm²) the basic mechanism of laser absorbing front propagation is the thermal conductivity in the weakly ionized fused quartz. In this case the laser absorbing front propagates with a speed of several meters per second [1,2] similar to the gas combustion under laser action [3]. At laser radiation intensity of the order of GW/cm² one can observe a regime of high-speed laser absorbing front propagation with impulsive pressure impact (~ 10 GPa) in the region of energy consumption. The arise of such high pressures localized inside the thin energy consuming zone leads to intense gas-dynamical processes, similar to that as it happens during metallic foil explosion inside condensed matter [4]. These intense gas-dynamical processes become to play a primary role in the overall evolution of the process. In this case one can observe experimentally a high-speed wave processes that cause the destruction of the medium and propagate with the speed ~ 2.6–3.2 km/s that is
sufficiently higher than that due to thermal conductivity but almost two times lower than sound speed in the cold fused quartz [1]. Considered experiments allowed to obtain the laser absorbing front and destruction wave velocities depending on the intensity of laser radiation [1, 5]. In addition the patterns of destruction were obtained. However all the experimental data provide only indirect information on the thermodynamics of the process, mechanisms of destruction, transport coefficients and kinetics of laser radiation absorption by the low-temperature dense plasma. Thus there is still not enough information to explain experimental observations and to provide physical model of the discharge propagation process. In this paper we have considered numerically a hydrodynamical mechanism of laser absorbing zone evolution to get additional qualitative information on the role of shock-wave and thermal processes. The obtained results should be useful for planning advanced experiments and understanding the non-hydrodynamic mechanisms of laser absorbing front propagation.

2. Problem setup and mathematical model

Consider the problem setup close to experimental one aimed to study the destruction of optical fibers under the action of intense laser radiation [1]. The laser pulse of 250 ns duration carries the radiation of 1.064 µm wavelength and maximum intensity of 4 GW/cm² changing in time according to first half-period of sinusoidal law with period 500 ns. Chosen intensity corresponds to the energy of 0.25 mJ acting on the core of optical fiber of 7 µm diameter.

We have assumed the following problem setup. The initial conditions contain the region of primal breakdown represented as heated zone of 40–800 µm length, and the radiation absorption begins on one of the margins of this region. The length of 40 µm corresponds to the characteristic size of deformed part of optical fiber estimated in [1, 5, 6]. Larger scales up to 800 µm are chosen to study independently the quasi-steady regimes in which there is no influence of rarefaction wave on the absorption front during the laser impulse action. It was assumed that dielectric breakdown took place as the radiation intensity achieved 2 GW/cm² that corresponds to the time instant of 40 ns for chosen form of impulse and is in agreement with estimation from [1]. As in [1, 5] there is no information about the temperature inside the primal breakdown region we considered cases with different initial temperatures.

Recently in [7, 8] it was proposed and confirmed both experimentally and theoretically that the absorption zone can be considered as a black body. Therefore we assumed that all the laser energy is absorbing inside a thin region representing a black body. On the one hand it is known that for correct evaluation of the radiation absorption phenomena inside dielectric materials one should take into account the temperature dependence of conduction electrons population. However it is also known that the absorption spatial scale can be estimated as an order of magnitude of laser wavelength that provides insufficient error in hydrodynamic calculations results. Herewith it was assumed that the laser radiation can be absorbed only by the medium at temperature greater than 1000 K.

Considering the laser absorbing front propagation inside optical fiber cable one can extract two natural directions–axial and radial. Almost all of the shock-wave processes generated by the absorbed laser energy evolve along the axial direction. Lateral rarefaction effects in the radial direction cause merely the attenuation of wave processes along the laser ray almost without any qualitative effects on the overall process evolution. Taking this issue into account the basic calculations were carried out in one-dimensional setup along the laser ray. It should be noted that the considered processes are characterized by high pressures and large spatial and time gradients of the parameters that demands using fully-conservative finite-differences Lagrangian schemes [9]. Construction of such a scheme is much easier for one-dimensional problems than for two-dimensional ones for which Eulerian coordinates are more suitable. In later case of Eulerian multi-dimensional models only non-conservative schemes are available that sufficiently reduce quality of computations in compare with Lagrangian one-dimensional fully conservative
approach. Therefore axially symmetric two-dimensional calculations were also carried out but only for getting the understanding of lateral processes and illustration of overall pattern of the process.

As the pressure rise inside the optical fiber under the action of high-intensity laser radiation achieve several GPa that is much greater than elastic-plastic and viscous (in liquid phase) stresses the dynamics of the medium can be described by the equations of ideal liquid with account of thermal diffusion and radiation absorption. Herewith, as the characteristic time scales of the considered problem are much larger than those of the energy and momentum exchange between electron and ion components (~ 1 ps), the hydrodynamics can be described using single-velocity single-temperature model. According to the problem setup applied here the equations representing the transfer of mass, momentum, energy and laser radiation inside optical fiber in Lagrangian coordinate system are following:

\[
\frac{\partial}{\partial t}\left(\frac{1}{\rho}\right) = \frac{\partial u}{\partial m},
\]

\[
\frac{\partial u}{\partial t} = -\frac{\partial p}{\partial m},
\]

\[
\frac{\partial \epsilon}{\partial t} = -p \frac{\partial u}{\partial m} + \frac{\partial}{\partial m} \left( \kappa \rho \frac{\partial T}{\partial m} \right) - \frac{\partial I}{\partial m},
\]

\[
\frac{\partial I}{\partial x} = -\alpha I,
\]

where \( \rho \) — the density, \( T \) — the temperature, \( p \) — the pressure, \( \epsilon \) — the internal energy, \( I \) — the intensity of laser radiation, \( \kappa \) — the thermal conductivity coefficient, \( \alpha \) — the radiation absorption coefficient, \( m \) — the mass coordinate (\( dm = \rho dx \)).

Thermal and dynamical processes evolution induced by the absorbed laser radiation alters the state of the fused quartz in a wide range of temperatures and pressures from normal conditions up to intense compression in a shock wave and heating up to the state of dense low-temperature plasma for which there are almost no thermodynamical data or transport properties. Taking into account the lack of information necessary for construction of wide-range equation of state, here we have developed a semi-empiric equation of state for fused quartz in a canonic form:

\[
P(\rho, T) = p_X(\rho) + p_T(\rho, T),
\]

\[
\epsilon(\rho, T) = \epsilon_X(\rho) + \epsilon_T(\rho, T),
\]

where \( p_X(\rho), \epsilon_X(\rho) \) and \( p_T(\rho, T), \epsilon_T(\rho, T) \) — the elastic and thermal components of pressure and internal energy correspondingly.

Equations of state (5)–(6) were elaborated on the basis of Hugoniot experimental data for fused quartz [10], experimental data on heat capacity at conditions near normal ones [11] and calculated heat capacities of silica in disordered phase (see figure 1). The later calculations were carried out using so-called chemical model of matter [12] and data from IVTANTHERMO database [13].

Elastic component of pressure at density higher than normal one \( (\rho > \rho_0, \rho_0 = 2.2 \text{ g/cm}^3) \) was developed on the basis of Mournagan–Birch equation of state based on the phenomenological theory of finite deformations [14]. Herewith, as the hydrodynamics calculations were carried out using Lagrangian formalism the deformations were also defined in Lagrangian coordinates, so the pressure dependence on density was represented by the polynomial law different to that presented in [15] where equation of state for silica near the phase transition was obtained:

\[
p_X(\delta) = A(\delta^{1/3} - \delta^{-1/3}) \left[ 1 - B \left( 1 - \delta^{-2/3} \right) \right] + p_0,
\]
where $\delta = \rho / \rho_0$, $A = 811.08$ GPa, $B = 0.586$ are empiric constants providing most accurate approximation of Hugoniot curves from [10].

In the rarefaction region, the elastic component of pressure was described in a form similar to van-der-Waals but with a Wohl’s correction for molecular attraction:

$$\tilde{p}_X(\delta) = -a\delta^2(1 - \delta) + p_0.$$  

(8)

Here constant $a$ was determined according to the equality of derivatives of $p_X(\delta)$ and $\tilde{p}_X(\delta)$ in the point $\delta = 1.0$. In (7) at density lower than that in critical point a faster tendency of pressure decrease with density was set, that lead to more rapid transition to the gaseous phase. Wherein decrease in pressure was still represented with polynomial law but with indexes 5/2 or 7/2. Thermal part of pressure value greatly exceeds elastic one in this range so the polynomial indexes do not play significant role.

Elastic part for internal energy was calculated as an integral of equations (7)(8) according to relation:

$$\epsilon_X = \int p_X / \rho^2 d\rho + \epsilon_0.$$  

(9)

Constants $p_0$ and $\epsilon_0$ were set to get correct values of pressure and internal energy of the fused quartz at normal conditions.

Thermal part of internal energy in the whole range of densities and pressures was calculated using the heat capacity. As for condensed media heat capacities at constant volume and constant pressure are close to each other, the heat capacity at constant pressure was used.

$$\epsilon_T = C_p T.$$  

(10)

Thermal part of pressure in the whole range of densities was calculated using the Grüneisen coefficient and internal energy:

$$p_T = \Gamma \rho \epsilon_T.$$  

(11)

At densities $\rho > \rho_0$ Grüneisen coefficient was calculated according to the linear interpolation between values for $\rho / \rho_0 \gg 1.0$ and $\rho / \rho_0 = 1.0$:

$$\Gamma = 1.05/\delta + 0.67(1.0 - 1.0/\delta).$$  

(12)
Figure 2. Hugoniot of the fused quartz. Calculated with equation (7) denoted with solid line, squares correspond to experimental data from [10].

Figure 3. Silica isotherms evaluated with equations (7)–(12). Lowest temperature value is 4000 K, temperature difference between adjacent isotherms is 250 K, solid line corresponds to the critical isotherm, critical point denoted with cross.

At the point $\delta = 1.0$, coefficients $\Gamma$ in (11) for $p_T(\delta > 1.0)$ and $p_T(\delta < 1.0)$ are the same. For $\rho/\rho_0 \ll 1.0$ Grüneisen coefficient was aimed to the value for monatomic gas.

Figure 2 represents Hugoniot curve for fused quartz in $p - \rho$ coordinates calculated according to (7) compare with experimental data from [10]. One can observe the only distinction in the vicinity of transformation to a denser stishovite-like state (at 20 GPa). This distinction does not exceed 10% by pressure. In the considered problem of optical fiber breakdown the pressure commonly is limited by the value of 10.0–15.0 GPa that is outside the noted region. Figure 3 shows isotherms in the range of specific volumes ($V = 1/\rho$) from $V = 0.5 \text{ cm}^3/\text{g}$ to $V = 10.0 \text{ cm}^3/\text{g}$ ($V_0 = 0.454 \text{ cm}^3/\text{g}$). The temperature range corresponds to the vicinity of critical point of liquid-gas phase transition which is determined from (7)–(12) as $V_{cr} = 1.5 \text{ cm}^3/\text{g}$, $T_{cr} = 4500.0 \text{ K}$, $p_{cr} = 0.68 \text{ GPa}$ and quite close to that obtained in [16] ($V_{cr} = 1.54 \text{ cm}^3/\text{g}$, $T_{cr} = 4862.0 \text{ K}$, $p_{cr} = 0.55 \text{ GPa}$). As it mentioned in [16] these values are determined with a large spread. The results obtained in this paper are within the scatter of these values.
The temperature dependence of heat capacity presented in figure 1 is approximated as:

\[ C_p = \chi \exp \left( \frac{s(0.01(T - T_{00}))^2}{\sigma^2} \right), \] (13)

where \( s = -1.0, T_{00} = 4000 \text{ K} \) for \( T < 7200 \text{ K} \) and \( s = 1.0, T_{00} = 7200 \text{ K} \) for \( T > 7200 \text{ K} \), \( \chi \) and \( \sigma \) are constant values providing the continuity conditions for heat capacity and its derivative at characteristic points (300 K, 4000 K, 7200 K, 15000 K, see figure 1). For temperature higher than 15000 K the slope of the heat capacity curve was set to achieve single-charge plasma heat capacity value at 30000–40000 K [3]. Taking into account the equations (7) and (13) the relation for thermal part of internal energy is following:

\[ \epsilon_T = \chi T \exp \left( \frac{s(0.01(T - T_{00}))^2}{\sigma^2} \right). \] (14)

Equation (14) can be regarded as the equation for temperature at given inner energy. In this case the temperature value can be obtained via iterative process.

Thermal conductivity coefficient for fused quartz was given by interpolation formula:

\[ \kappa = \begin{cases} 
1.36 \times 10^5(T/300)^{0.2897}, & T \leq 40000 \text{ K}, \\
55.5(T/1000)^{2.5}, & T > 40000 \text{ K}.
\end{cases} \] (15)

Chosen dependence adequately approximates experimental data up to 1100 K [11] and matches well with thermal conductivity coefficient of singly ionized gases at temperature about \( \sim 40000 \text{ K} \) [3].

Due to lack of information about the radiation absorption in a wide range of laser radiation intensities the absorption coefficient was modeled as:

\[ \alpha = \frac{1}{D} \left( \frac{T}{1000} \right)^{1.5}. \] (16)

Here the temperature dependence of the coefficient is chosen similarly to the braking absorption in plasma, and characteristic absorption length was varied in a range from 1.0 to 10.0 \( \mu \text{m} \). Here with \( D = 1.0 \mu \text{m} \) was chosen as a basic one.

3. Numerical methods

One-dimensional calculations of shock-wave processes in silica were carried out in Lagrange coordinates using a fully conservative finite difference scheme. When studying intense pulse processes one usually utilize the scheme presented in [9]. The advantage of fully conservative scheme is that independently on the choice of spatial and time steps the conservation of full energy provides correct balance between internal and kinetic energies [9]. For problems with large spatial and/or time gradients this issue is crucial as the error related with unbalanced energy terms could be sufficiently large even on high resolved spatial grid. The canonic numerical scheme presented in [9] is implicit and demands to perform resource intensive iterative process that can sufficiently increase the calculation time. Here we used the predictor-corrector scheme that satisfies the conditions of total energy conservation and occurs to be more efficient compare with canonic implicit scheme [9]. Short description of this scheme is presented in Appendix.
Figure 4. Temperature dependence of velocity of sound in silica medium at normal density. Solid line is calculated from equations of state (5)–(12), dash-dotted line is calculated via medium chemical model taking into account incomplete molecular dissociation, dashed line is calculated with ideal gas equation of state.

4. Results of numerical analysis

4.1. Task parameters
Considering the dynamical processes arising inside the fused quartz under the action of intense laser pulse one can extract two basic factors governing this processes: (1) energy transfer out from the radiation absorption zone by means of thermal conductivity and (2) mass, momentum and energy transfer by means of gas-dynamical transport. The fundamental parameter characterizing the gas-dynamical processes inside medium is velocity of sound. At normal conditions the sound velocity scales for fused quartz are well-known [17]: $c_{\text{long}} = 5570$ m/s (longitudinal sound velocity), $c_{\text{cross}} = 3430$ m/s (transversal sound velocity) and $c_{\text{stem}} = 5370$ m/s (sound velocity in a stem). The equations of state (5)–(12) provide the value $c_s = 5000$ m/s that is of the order of magnitude of the real one. Quantitative error does not exceed 10% that should not influence sufficiently the obtained qualitative results. It should be also noted that in the range of high pressures and temperatures intrinsic to the considered problem setup the sound velocity differs considerably from that at normal conditions. At the temperatures higher than the ionization limit sound velocity becomes close to the sound velocity of low-temperature plasma. Figure 4 represents the calculations of sound velocity at temperature higher than evaporation limit using different methods. Present model provides results on average between assumption of ideal gas equation of state and results of chemical model [18]. At relatively low temperatures present results are close to the assumption of ideal gas which corresponds to fully dissociated medium. At high temperatures it aims to the results of chemical model correct for real compound of discharge products. Meanwhile all the approaches presented in figure 4 provide close results, and it can be seen that the sound velocity in the heated silica is almost twice lower than one in cold silica. It is obvious that exactly this velocity scale should determine the gas-dynamical processes inside the region of intense radiation absorption.

Consider in details the evolution of gas-dynamical processes inside the region of laser radiation absorption. As it was already mentioned above the initial conditions are following: the primary breakdown has been already realized and the laser radiation intensity has achieved 2.0 GW/cm$^3$ that is high enough to provide condition for breakdown and correspond to the time instance of 40 ns from the beginning of the pulse action. In all the calculations the region of primary breakdown was modeled as a region of medium with normal density ($\rho = 2.2$ g/cm$^3$) at increased
Figure 5. Wave pattern on the quasi-steady initial stage of the process: shock wave (1) propagating out from the breakdown region and thermal wave generated by radiation absorption in the region (2, 3). Pressure is denoted with black line, temperature with red line and silica mass velocity $u$ with blue one. Profiles are presented at time instant of 100 ns from the beginning of the pulse action (60 ns from the beginning of the radiation absorption process). Temperature inside the breakdown region equals to 5000.0 K.

temperature. In assumption that all the absorbed energy was transformed into heating of the initially non-transparent region the temperature of primary breakdown region can be estimated as 1500–4000 K. At the same time there is almost no information about the real temperature value achieved inside the optical breakdown. Usually one assumes it to be of the order of 10000 K. Taking this into account a set of calculations with initial temperatures inside breakdown region varied in a range from 1500 to 15000 K was performed for more detailed analysis of hydrodynamic factors impact on the overall process.

One-dimensional heated region of primary breakdown is bounded by two contact surfaces, one of which (right) was faced towards the laser ray. On this right contact surface an energy absorption began inside the Lagrangian particles with temperature higher than 1000 K. During approximately 5 ns after thermal discontinuity decay on the breakdown region bounds one can observe the shock waves propagating in both directions out from the primary breakdown region. At this early stage the radiation absorption took place directly behind the shock front propagating towards the laser beam. As expected the shock wave speed exceeded the sound velocity in cold silica and increased with initial temperature inside the primary breakdown region. After a short period the gap between the leading shock wave and absorption front increased sufficiently, and the temperature behind the shock wave raised relatively weak not reaching silica melting point. Thus we observed a stable wave structure (see figure 5) consisting of (1) leading shock wave, (2) zone of hydrodynamic flow of cold silica slightly heated behind the leading shock and assumed to be transparent for laser radiation and (3) zone of energy absorption characterized by the temperature local sharp increase. This structure sustained up to the time instant when the rarefaction wave outrun the energy absorption zone from behind.

4.2. Quasi stationary stage

For qualitative understanding of the extracted stages of process evolution and the transitions between them let us consider the case in which the early quasi stationary stage lasts relatively
long period of time (initial breakdown region in this case is of 800 μm length). Figure 5 represents a typical wave pattern described above long before the rarefaction wave outruns the energy absorption zone (temperature inside the primal breakdown region was 5000 K). In the considered case the shock wave speed has the constant value of 5200 m/s during the whole observed period of time, which is not much more than velocity of sound at normal conditions given by considered model equation of state, so the shock wave is close to acoustic wave. Histories of maximum temperature inside the energy absorption zone and thermal wave speed for this case are presented in figure 6. At time 125 ns the intensity of laser impulse passes through its maximum and at time 165 ns the rarefaction wave outruns the energy absorption zone whereupon (at time 180 ns) temperature inside absorption zone and laser absorption front (or thermal wave) velocity drop sharply. It is seen from figure 6 that laser absorption front achieves a quasi steady propagation regime with speed of 720 m/s during the period of ∼ 100 ns. It should be also noted that the mass velocity in the region behind the shock front equals 700 m/s and almost constant until the rarefaction wave arrival at time ∼ 170 ns (see figure 6). Taking into account that the laser absorption front propagates both due to the thermal conductivity and due to the convective transport in flow formed behind the shock front, the speed of energy transport via thermal conductivity mechanism can be estimated as 20 m/s. This velocity scale is not sufficient compare with all the experimentally observed velocities, therefore it can be preliminary concluded that thermal conductivity mechanism play almost no role in evolution of considered high-speed regimes. As the rarefaction wave outruns the energy absorption zone the speed of laser absorption front along with temperature of the medium inside absorption zone decreases sharply that can be treated as a trigger of change in the governing mechanism of the laser absorption front propagation in the experimental research. After the rarefaction wave intersects the contact surface formed by the energy absorption zone and the thermal wave front a tendency of fast pressure decrease even down to negative values can be observed. These negative pressure values indicate the medium continuity destruction (or spallation). Within the framework of considered simplified one-dimensional problem setup and the absence of correct equation of state inside the spallation region the emergence of negative pressures can be treated only as a qualitative tendency of further process evolution.

In case of 10000 K inside the primal breakdown region the shock wave speed, mass flow velocity behind the shock front and the thermal wave speed are correspondingly $U_s = 5750$ m/s, $u = 1080$ m/s and $U_t = 1100$ m/s. For 2000 K, they are $U_s = 5040$ m/s, $u = 270$ m/s and $U_t = 290$ m/s. One can conclude that velocity of laser absorption front propagation is

![Figure 6](image-url)
determined mainly by the convective flow velocity behind the shock wave, and the convective mechanism becomes more pronounced with rise of the initial temperature inside the primal breakdown zone, while thermal conductivity of the absorbed laser energy provides only 20 m/s additional velocity relative to mass velocity of the flow formed behind the shock wave in all considered cases. Opposite to the regimes considered here one can also observe slow regimes of laser absorption front propagation at relatively low laser intensities [5]. In such cases it is reasonable to assume that the thermal conductivity plays a leading role in laser absorption front propagation. In view of this characteristic velocity scale corresponding to the thermal conductivity is almost twice higher compare with that obtained experimentally [5] which can be resulted both from higher temperature gradient inside laser absorption front and from one-dimensional approximation which does not take lateral thermal losses into account. At the same time one can observe underestimation of the overall radiation absorption zone velocity compared with experimental values [1, 5] even in cases with explicitly overheated primal breakdown zone. This suggests that gas-dynamical transport is not the key mechanism that governs propagation of radiation absorption zone in the optical breakdown process even for quasi-stable one-dimensional regime without the lateral losses.

4.3. Non-steady stage

Let us consider now the case when the length of the primal breakdown region is small enough so gas-dynamical perturbations could pass it much faster than laser pulse duration. Due to small spatial scales quasi stable stage of the process do not have time to develop in contrast with abovementioned cases of larger lengths of the primal breakdown region. Flow structure in this case is determined by the rarefaction waves generated by the medium expansion and by the perturbations propagating from the radiation absorption zone. Figure 7 represents development of the process at the time 20 ns after the absorption begins. Primal breakdown region length along the fiber axis is 40 µm that is close to obtained experimentally in [1, 5], initial temperature is equal to 1500 K. Shock waves generated by the discontinuity decay on the margins of the primal breakdown region propagate through cold medium in opposite directions with velocity values close to velocity of sound at normal conditions. Breakdown zone expansion is asymmetric unlike freely expanding heated medium as the region of intense energy input is localized only on the one side of the breakdown zone that is closer to the radiation source. Part of the medium ahead the propagating breakdown region is more compressed and moves towards radiation source with higher mass velocity \((u_2 > u_3,\) as it signed in figures 5 and 7). On this initial stage which lasts 10 ns in considered case process evolution inside radiation absorption zone almost the same as in quasi-stable regime examined before (and presented in figure 5). Temperature in the absorption zone is continuously increasing. And as a result regions with different acoustic impedance are formed. Acoustic impedance in absorption zone is lower as both sound velocity and density are lower than that in surrounding medium. Mass velocity near the absorption zone is directed from left to right towards laser radiation source. On the right of the absorption zone the medium with lower acoustic impedance (heated in the absorption region) is moving towards medium with higher impedance that results in formation of weak compression wave. On the contrary on the left side of absorption zone medium with lower impedance (from the region of initial breakdown) flows to a medium with higher impedance that leads to rarefaction. Thus the initial stage of medium expansion out form the energy deposition zone is characterized by the mass velocity decrease on the left and the increase on the right of the absorption zone (that can be vividly seen in figure 5).

Later after 5.0 ns (that is 15.0 ns from the absorption start) rarefaction expanding from the middle of the breakdown region comes into the absorption zone. Density inside absorption zone sharply decreases resulting in brief temperature increase from 4100 K to 7400 K which vanishes during next several nanoseconds. From now further evolution of the absorption zone is related
with its hydrodynamic extension, and one can observe a sharp increase of the difference between mass velocities on the opposite boundaries of the absorption zone (see figure 7c) compare with that observed on the initial stage. Finally the absorption zone becomes the margin between oppositely directed flows. The hydrodynamic extension causes additional expansion of the heated region, which at time instant of 20 ns increases up to 16.0 μm compare with 1.5 μm observed on the initial stage. On the relatively small temporal scales of the extension process negative elastic pressure cannot be compensated by the rise of the pressure thermal part and as a result negative pressure inside absorption zone reaches 4.6 GPa already after 20 ns from the beginning of absorption and continues to increase. Finally it should lead to the medium

**Figure 7.** Effect of laser radiation absorption on the margin of the initial breakdown region with 40 μm length and 1500 K temperature. Spatial distribution of the pressure (a), temperature (b) and mass velocity (c) at time instant of 60 ns from the beginning of the pulse action (20 ns from the beginning of the radiation absorption process). Dashed lines–properties at the initial moment, solid lines–at time instant of 60 ns. Negative pressure observed in the radiation absorption region at 60 ns and reaching the value of 4.6 GPa is not presented.
continuity destruction (spallation) that could not be correctly described in a framework of the used continuum mechanics approach.

Calculation results shown that for initial breakdown parameters observed in real experiments (breakdown region length is about 20–30 µm, initial temperature is in the range of values from 1500 K to 2000 K) it takes no more than 10–15 ns for rarefaction wave propagating from the middle part of the breakdown region to achieve absorption zone. At mass velocity about 150–200 m/s the laser absorption front propagation due to gas-dynamical transport until the moment of high negative pressures emergence can be estimated as not exceeding 30 µm. It is evident that as the overall pulse duration is much longer the contribution of gas-dynamical effects in total velocity of the laser absorption front cannot be significant.

5. Conclusions
In present study the qualitative pattern of the laser absorption front propagation process was proposed basing on gas-dynamical model of the local energy input in fused quartz medium without focusing on the diversity of governing physical processes. Simplified problem setup considered here had no intention for detailed reproduction of the certain experimental setups and was aimed only on qualitative estimation of shock-waves propagation and thermal effects contribution in dynamics of the laser absorption front propagation. Calculations were carried out taking into account medium properties obtained with experimental data as it was discussed above in section 2. Obtained results allowed us to emphasize following fundamental features of the laser absorption front propagation process evolution.

Temperature inside initial breakdown region should be enough to provide radiation absorption on free electrons that result in significant increase of pressure inside the absorption region. Sharp pressure increase leads to shock wave formation on the right margin of the primal breakdown region that propagates towards laser source. Temperature behind the shock wave is close to the normal one so compressed medium is assumed to remain transparent for radiation. Radiation absorption begins on the contact surface of the heated layer and further localizes in the flow behind the shock wave until the rarefaction wave overcomes absorption zone. On this stage process evolution is quasi-stationary and velocity of absorption region towards radiation source is determined mainly by the mass velocity of the flow behind the shock wave. Heat conduction also affects the thermal wave velocity but its contribution is by the order of magnitude less than the velocity of gas-dynamical transfer. Temperature inside absorption zone is increasing monotonically with radiation intensity rise while pressure almost equal to that behind the shock wave. Conditions corresponding to spallation are not observed on that stage. Thus convective absorption zone transfer behind the shock wave apparently could significantly contribute to velocity of laser absorption front propagation in case of quasi-stable regime formation. In this case velocity of the optical fiber breakdown wave should exceed hundreds of meters per second which is much more than thermal wave velocity but still lower than that observed experimentally.

Quasi-stationary stage is terminated with rarefaction wave arrival to the absorption region. According to analysis of this case performed in section 4 sharp gradients of thermodynamical and dynamical properties arise inside the absorption zone that should lead to the medium continuity destruction. Although it is impossible to model properly the process in framework of used continuum mechanics approach, it can be expected that it is the stage that finally leads to microstructural changes in the medium and formation of cracks and cavities.

As gas-dynamical process of laser absorption front propagation is realized only until rarefaction wave arrival to the boundary of absorption region, its existence depends entirely on the duration of rarefaction wave transfer inside primal breakdown region. Thus if initial length of the breakdown region is such that the time required for acoustic wave transfer is lesser than duration of shock wave formation on the margin of the region then quasi-stable regime and absorption zone gas-dynamical transfer have no time to be realized. Process
evolution for that case is given in section 4 where it is shown that for experimentally observed breakdown regions with small length the effect of gas-dynamical transfer on the laser absorption front velocity is insignificant. Thus the role of gas-dynamical processes in formation of laser absorption front velocities observed in natural experimental environment apparently has to be also negligibly small and become even smaller with taking into account the lateral rarefaction. At the same time gas-dynamical rarefaction waves generated by intense energy input can provide conditions sufficient for silica continuum destruction inside the absorption zone and developing of microstructural defects propagating towards radiation source with speed close to volumetric sound velocity as it was shown previously. Formulated mechanism of the breakdown propagation is a subject for further research.

Acknowledgments
The work was funded by the grant of the Russian Science Foundation No. 14-50-00124.

Appendix. Fully conservative Lagrangian method predictor-corrector
Approach can be utilized for solving problems in multidimensional coordinate systems however Lagrangian representation is essential. Let us briefly describe numerical scheme on the example of finite-difference approximation of equations (1)–(3).

All thermodynamical parameters (such as density, pressure, internal energy and temperature) are defined in the middle of the cells while velocities and coordinates are defined in the nodes of the numerical grid. In that case fully conservative Lagrangian numerical scheme could be developed in a predictor-corrector form given below. For simplicity only time derivatives are presented (time steps numbers are denoted by superscripts). All spatial derivatives in equations (1)–(3) are approximated via common central differences.

\[ x^{n+1/2} = x^n + 0.5\tau u^n, \]  
\[ V^{n+1/2} = V^n + 0.5\tau \left[ \frac{\partial u}{\partial m} \right]^n, \]  
\[ \epsilon^{n+1/2} = \epsilon^n - p^{n+1.2}(V^{n+1/2} - V^n) + 0.5\tau \left[ \frac{\partial}{\partial m} \left( \kappa \rho \frac{\partial T}{\partial m} + \alpha I \right) \right]^n, \]  
\[ u^{n+1} = u^n - \tau \left[ \frac{\partial p}{\partial m} \right]^{n+1/2}, \]  
\[ x^{n+1} = x^{n+1/2} + 0.5\tau u^{n+1}, \]  
\[ V^{n+1} = V^{n+1/2} + 0.5\tau \left[ \frac{\partial u}{\partial m} \right]^{n+1}, \]  
\[ \epsilon^{n+1} = \epsilon^{n+1/2} - p^{n+1.2}(V^{n+1} - V^{n+1/2}) + 0.5\tau \left[ \frac{\partial}{\partial m} \left( \kappa \rho \frac{\partial T}{\partial m} + \alpha I \right) \right]^n. \]  

Here \( \tau \) denotes time step and \( V = 1/\rho \) is the specific volume.

It should be noted that in equations system (1)–(7), the third and the last equations are implicit. In (A.3) pressure and energy are set on the one step and its solution requires iterative procedure. However in our case thermal part of the pressure depends linearly on temperature so (A.3) is resolved explicitly. The last equation of the system is implicit due to terms with thermal conductivity and energy absorption. Here we utilized common tridiagonal matrix algorithm for its solution [19]. However as Courant–Friedrichs–Lewy condition imposes sever restriction on the time step value it was found that contributions from thermal conductivity and energy absorption could be accounted on previous time step that makes equation (A.7) explicit.

References
[1] Dianov E M et al 2006 JETP Lett. 83 84–88
[2] Gorbachenko V I et al 2010 Dokl. Akad. Nauk 433 618–621
[3] Raizer Y P 1974 Laser Spark and Discharge Propagation (Moscow: Nauka)
[4] Tkachenko S I, Levashov P R and Khishchenko K V 2006 J. Phys. A: Math. Gen. 39 7597–7603
[5] Efremov V P, Fortov V E and Frolov A A 2015 J. Phys.: Conf. Ser. 653 012013
[6] Bufetov I A and Dianov E M 2005 Phys. Usp. 175 100–103
[7] Carr C W et al 2004 Phys. Rev. Lett. 92 087401
[8] Duchateau G, Feit M D and Demos S G 2012 J. Appl. Phys. 111 093106
[9] Popov Y P and Samarskii A A 1969 Zh. Vychisl. Mat. Mat. Fiz. 9 953–958
[10] Marsh S P 1980 LASL Shock Hugoniot Data (Los Alamos Scientific Laboratory Series on Dynamic Material Properties vol 5) (Univ. California Press)
[11] Grigoriev I S and Meylikhov E Z 1991 Fizicheskie Velichiny (Moscow: Energoatomizdat)
[12] Gryaznov V K et al 1998 J. Exp. Theor. Phys. 114 1242–1265
[13] Belov G V, Iorish V S and Yungman V S 2000 High Temp. 38 191–196
[14] Zharkov V N and Kalinin V A 1968 Equations of State for Solids Under High Pressures and Temperatures (Moscow: Nauka)
[15] Petrovtsiev A V et al 2006 AIP Conf. Proc. 849 380–392
[16] Iosilevskiy I, Gryaznov V and Solovev A 2014 High Temp.–High Pressures 43 227–241
[17] Kikoin I A 1976 Tablicy Fizicheskikh Velichin (Moscow: Atomizdat)
[18] Ebeling W et al 1991 Thermophysical Properties of Hot Dense Plasmas (Stuttgart–Leipzig: Teubner)
[19] Chung T J 2002 Computational Fluid Dynamics (Cambridge Univ. Press)