Dynamics of laser plasma convective plume in high pressure xenon

M A Kotov, S Yu Lavrentyev, N G Solovyov, A N Shemyakin, M Yu Yakimov
A. Ishlinsky Institute for Problems in Mechanics RAS, 101-1 Vernadskogo Ave., Moscow, Russia, 119526
E-mail: kotov@ipmnet.ru

Abstract. This paper presents the results of numerical simulation of convective plume pulsations from a concentrated heat source equivalent to a continuous optical discharge (COD) in high pressure xenon compared to originally obtained experimental results. Simulated dynamic distributions of temperature, density and velocity of the gas around small spheroidal heat release zone are obtained, showing the process of formation of toroidal vortices in the convection zone, leading to the appearance of pulsations. The simulation results are qualitatively and quantitatively consistent with previously obtained experimental data.

1. Introduction
Continuous optical discharge (COD) is one of the methods for sustaining plasma with a temperature close to that of complete single ionization, which does not require structural elements, electrodes, waveguides, inductors or ducts to supply energy to the plasma. This allows sustaining plasma, for instance, in closed quartz bulbs filled with high-pressure rare gas by supplying laser radiation through a transparent wall. This principle is the basis for the high brightness broadband laser-plasma radiation sources based on COD and widespread in recent years [1, 2, 5].

One of the main requirements for sources like that is high temporal and spatial stability of radiation [3–5]. Nevertheless, even if all the parameters are completely stabilized, the presence of COD plasma causes convection in the plasma forming gas followed by characteristic pulsations that negatively affect stability of COD plasma position and brightness [3, 4]. To cure this problem special measures have to be taken, which are not always successful and often difficult to implement [5].

At different times, various physical mechanisms that could serve as the cause of self-oscillations of COD were considered and put forward as the main ones in specialized literature. This paper presents the results of numerical simulation of pulsations of a convective plume from a concentrated heat source equivalent to COD. A comparison of the results of numerical simulation with experimental results obtained earlier under conditions close to set ones proves the hydrodynamic nature of the instability under consideration.

2. Preliminary studies
Just in the first experiments on initiating and sustaining COD, plasma self-oscillations were detected, and associated with pulsations of the thermal gravity convection plume [6].

For the first time, this type of COD self-oscillations was studied in detail in [10]. Authors observed and recorded (by Schlieren technique) the oscillating convective plume from COD, sustained by the...
radiation of a CW CO₂ laser in a discharge chamber with xenon at a pressure of 3-5 bar and with argon in a wider pressure range of 3-23 bar.

Authors of [10] associate the observed pulsations with frequencies of 19-33 Hz with the high temperature front instability of the optical discharge (the so-called laser combustion wave) in the oncoming gas flow. Nevertheless, as was soon proved in [11], the laser combustion wave under considered conditions of free convection flow is fundamentally stable. Therefore, the explanation of the pulsation mechanism proposed in [10] appeared to be incorrect.

The general rule formulated in [11] allows for exceptions in some special cases. In a whole series of studies, COD pulsations arose due to inhomogeneity of gas flows blowing around the plasma or the simultaneous action of absorption and refraction of laser radiation supporting the plasma, in particular, taking into account refraction at the boundary of the convection zone [7–9], however, the results of these studies do not explain the nature of regular convective plume oscillations.

In [4], pulsations of COD convective plume in xenon were studied in the pressure range of 15-40 bar, which is used in high brightness broadband radiation sources. Based on the observations, a simple physical model was proposed that describes the experimental dependence of the pulsation frequency on pressure. It was also shown in the paper that an increase in the pulsation frequency from 39 to 52 Hz with increasing gas pressure in the above range obeys the similarity law

\[ f = 0.5(g/2r)^{1/2}, \]  

where \( f \) is the oscillation frequency, \( g \) is the acceleration of gravity, and \( r \) is the minimum radius of the front of the heated gas around COD, forming the head of an oscillating convective plume. Similar data [10] also fit well on the line (1).

As it was noted in [4], the similarity law (1) practically coincides with the analogous law for flickering diffusion flames, such as pool flames or premixed flames burning at low feed rates [13–15]. For the final solution of the problem, it is useful to carry out numerical simulation of the dynamics of convective plume from a concentrated heat source, equivalent to COD in terms of the size of the heat release zone and thermal power. With this formulation of the problem, the class of instabilities arising from the interaction of laser radiation with plasma followed by oscillations [7-9] is excluded.

3. Formulation of the problem

A convective plume of gas heated to a high temperature originates around COD plasma sustained due to absorption of laser radiation. The plume is formed as a result of heat transfer (by means of thermal conductivity and convection in part) to the surrounding gas from the discharge zone and thermal gravitational convection. Due to this mechanism of heat energy removal, the plasma in typical conditions loses about one fifth of the power of the incident laser radiation [1].

In numerical simulation, the hydrodynamic convection problem is solved around a local heat source in high-pressure xenon (17-50 bar) located in a spherical quartz bulb with a diameter of 16.62/20.62 mm (ID/OD), the temperature of outer surface of which is considered to be constant of 500 K. It is assumed that in a small volume in the form of an elongated spheroid with a diameter of 0.3 mm and 0.5 mm long located in the center of the bulb, a thermal power of 10 W is released. The statement of the problem basically corresponds to the conditions for sustaining COD in a laser-plasma high brightness radiation source LPS-50 [2] with total laser radiation power of 50 W.

4. Solution method

The problem was solved using the ANSYS CFX hydro aerodynamics numerical simulation software package [15]. A non-stationary system of Navier-Stokes equations for a compressible gas in a gravitational field was solved, similar to [16], with the exception of terms related to the plasma and plasma interaction with laser radiation. The power density and the total heat release power were considered to be constant in a fixed energy release region. The necessary dependences of the density,
thermal conductivity, heat capacity and viscosity of xenon on temperature and pressure in the range from $300 \, ^\circ K$ to $15 \, kK$ are taken from [17].

The solution to the convective plume problem close to stationary one was used as an initial condition for solving a dynamic problem. Due to the initial conditions, it was possible to reduce the calculation time at which the plume oscillations had time to develop to several periods of oscillations (see fig. 3).

**Figure 1.** Comparison of several phases of one pulsing period presented in dark field schlieren patterns of convective plume from COD at $50 \, W$ input laser power in Xe, $p = 20 \, \text{bar}$ [4] with corresponding phases of simulated pulsing period at $10 \, W$ released power in Xe, $p = 29 \, \text{bar}$, presented in color pictures to the right from corresponding dark field patterns. Difference of time marks corresponds to the difference in oscillation periods. Frame sizes are close to $3 \times 5 \, \text{mm}^2$.

**Figure 2.** Isotherm $3 \, kK$ radii variations for one pulsation period. Dots correspond to experimental cross sectional ($Y=0$, red color) and axial ($X=0$, blue) radii of isotherm, shown in dark-field photos from fig. 1. Lines represent cross sectional (red) and axial (blue) radii of corresponding simulation results also presented in fig. 1.
Since the gas temperature did not exceed 8 kK outside small vicinity around given energy release region, the effects related to the presence of free electrons, ions and radiation heat transfer could not have noticeable effect on the result. When solving this problem, those effects were taken into account indirectly, through the given initial and boundary conditions, as well as temperature dependences of gas parameters.

5. Solution results and discussions

The dynamic distributions of the temperature, density and velocity of the gas around the heat release zone were calculated for three values of the pressure established during gas heating in a closed volume 

\[ p = 29; 48; 50 \text{ bar}. \]

Fig. 1 represents the time phases of one pulsation period obtained experimentally in the form of the dark field schlieren patterns of the convective plume from COD at laser input power of 50 W in Xe, \( p = 20 \text{ bar} \) [4].

For comparison, next to them there are density distributions in conventional colors, calculated in domains of the size close to experimental ones, corresponding to the same phases of the simulated pulsation period at a thermal power of 10 W in Xe, \( p = 29 \text{ bar} \). The light lines in the dark field experimental images correspond to surfaces of maximum refractive index (proportional to the gas density) gradient of the gas approximately corresponding to 3 kK isotherm. In conventional color images, red corresponds to a maximum density of more than 90 kg/m\(^3\), blue - to a minimum density of less than 10 kg/m\(^3\), intermediate values are shown in shades of yellow, green and blue in decreasing order of density. Color images of the density distribution to the right of the dark field patterns correspond to the same pulsation phase. Different time marks of the same phases indicate a difference in the oscillation period. The dimensions of slightly different in size dark field frames and color frames are approximately 3x5 mm\(^2\). It can be seen that the simulation gives a pulsation patterns close to experimentally observed ones.

In fig. 2, a quantitative graphical representation of the similarities and differences between the experimental data and the results of numerical simulation is shown. Fig. 2 provides a comparison of the variations of the simulated and measured radii of the 3 kK isotherm for one pulsation period. The points correspond to the experimental values, the lines represent the results of numerical simulation. Radius of 3 kK isotherm in the direction of the vertical axis Y is shown in blue and that in the direction of the horizontal axis X passing through the center of COD in red. The arrangement of the axes with respect to the plasma and 3 kK isotherm is schematically shown on the right to the graph.

![Figure 2](image)

**Figure 2.** The process of establishing a periodically oscillating solution to a dynamic problem using the example of a convective plume diameter for \( T = 3 \text{ kK} \) isotherm in a horizontal section \( y = 0 \) passing through the center of the energy release computational domain. The pressure conditions are indicated on the left, corresponding oscillation frequencies estimated at the end of the simulation time domain 0.1 s are presented on the right.

**Figure 3.** The process of establishing a periodically oscillating solution to a dynamic problem using the example of a convective plume diameter for \( T = 3 \text{ kK} \) isotherm in a horizontal section \( y = 0 \) passing through the center of the energy release computational domain. The pressure conditions are indicated on the left, corresponding oscillation frequencies estimated at the end of the simulation time domain 0.1 s are presented on the right.
Obviously, there is a qualitative similarity in the nature of the change in both parameters over the period. The quantitative difference is shown in fig. 2 by the difference in scales along the axes of the graph, corresponding to the experimental and simulation cases. The pulsation amplitude that is smaller 2.45 times in horizontal and 3.7 times in vertical direction in the experiment as compared to the simulation ones, probably occurs due to the presence of an additional vertical component of the cold gas velocity at the entrance to the convection region, which is not taken into account in numerical simulation.

The same factor is probably responsible for the difference in the oscillation frequencies (32 Hz in the simulation case and 43 Hz in the experimental case), which is shown in the graph in fig. 2 by different time scales along the bottom and upper axes respectively.

Fig. 3 depicts the process of establishing fluctuations in the plume diameter from the isotherm \( T = 3 \) kK. It can be seen that the higher is the pressure, the faster is the process of establishing the oscillatory regime of the plume and the higher is resulting frequency. Dynamic calculations were artificially limited by a time of 0.1 s, since this was sufficient to verify the operability of the computational model. Nevertheless, beyond this time domain, the gas flow regime will further be establishing in whole spherical volume followed by further change of the oscillation frequency.

**Figure 4.** The time phase (“-3 ms”, as marked in fig. 1) calculated distributions (in conventional colors) of temperature a), velocity b), density c) around the center of simulation domain compared to d) dark field schlieren image of corresponding oscillation phase of COD convective plume (isolines of refractive index gradient) in Xe, \( p = 20 \) bar [4]. The ellipses of 0.3x0.5 \( \text{mm}^2 \) indicate heat release zone and position of COD. The frame size is 3x5 \( \text{mm}^2 \) except for b) 5x5 \( \text{mm}^2 \).

In fig. 4 a), b), c) two-dimensional distributions are shown, respectively, of temperature (0.5-13 kK), velocity (0-1 m/s) and density (3-97 kg/m\(^3\)) in shades of five basic conventional colors, red color corresponds to the maximum, and blue – to the minimum value of the parameter. The distributions were obtained at a pressure \( p = 29 \) bar at a time mark of 0.09 s of the calculated range. Fig. 4, d) shows on the same scale the experimental [4] schlieren patterns of COD convective plume in the pulsation phase close to the calculated distributions. One can see a good qualitative and close quantitative correspondence of the distributions of Fig. 4, c) and d). In fig. 3, b), the arrows show the directions of the gas velocity vectors in the convection zone. The frame displays the pulsation phase, in which the formation of a toroidal vortex at the lower boundary of the hot gas and the separation of the developed vortex from the main convective flow in the upper part of the frame occur simultaneously. Repetitive process of formation, rising and separation of toroidal vortices from main convective flow leads to pulsation. In Fig. 4, d) the presence of a developed vortex in the upper part of the field can be judged by the branching of lines showing the boundaries of hot and cold gas, corresponding to the entrainment of the colder surrounding gas in a hot convective stream accordingly to the direction of the gas rotation in the vortex.

On the whole, based on the qualitative and quantitative correspondence of the results of hydrodynamic modeling, the experimental data allow drawing a conclusion on purely hydrodynamic
nature of the instability which causes regular oscillations of the convective plume and plasma in the case of continuous optical discharge.

The discrepancies between simulation results and experimental data manifest themselves in the underestimated pulsation frequencies in simulation as compared to the experimental data [3, 4] and related difference in the pulsation amplitudes near the head of the convective plume as demonstrated on the plot in fig. 2. A possible reason for the discrepancies is insufficient computational time to establish the regimes of the convective plume and velocity field in the whole computational volume.

Conclusions

It has been found that COD plasma regular pulsing with characteristic frequency increasing with pressure occurs due to hydrodynamic effects during thermal gravitational convection. Numerical simulation based on purely hydrodynamic convection model gives gas density, temperature and velocity dynamic distributions that in main features correspond to the experimentally observed pulsing of real COD convective plume under close conditions. Thus the conclusion can be made that the reason for the regular oscillations of COD convective plume and plasma is of hydrodynamic nature.

Acknowledgements

The authors are grateful to N.M. Yakimov (MAI (NRU), BMSTU) for his kind assistance in setting the problem and making calculations. The work was carried out under the government contract #AAAA-A20-120011690135-5.

References

[1] Zimakov V P, Kuznetsov V A, Solovyov N G, et al. 2014 Physical and Chemical Kinetics in Gasdynamics 15(5) http://chemphys.edu.ru/issues/2014-15-5/articles/247/
[2] Zimakov V P, Kuznetsov V A, Lavrentyev S Yu, Solovyov N G, Shemyakin A N, Shilov A O, Yakimov M Yu 2016 Physical and Chemical Kinetics in Gasdynamics 17(2) http://chemphys.edu.ru/issues/2016-17-2/articles/653/
[3] Zimakov V P, Lavrentyev S Yu, Solovyov N G, et al. 2018 Physical and Chemical Kinetics in Gasdynamics 19(4) http://chemphys.edu.ru/issues/2018-19-4/articles/754/
[4] Lavrentyev S.Yu., Solovyov N.G., Shemyakin A.N., Yakimov M.Yu. 2019 J. Phys.: Conf. Ser. 1394 012012 https://iopscience.iop.org/article/10.1088/1742-6596/1394/1/012012/pdf
[5] Antsiferov P S, Koshelev K N, Krivtsun V M, Lash A A 2016 Patent US #9357627 B2
[6] Generalov N A, Zimakov V P, Kozlov G I, Masyukov V A, Raizer Yu P 1972 Sov. Phys. JEPT 34 763
[7] Gerasimenko M V, Kozlov G I, Kuznetsov V A 1980 Soviet Technical Physics Letters 6 208
[8] Generalov N A, Zakharov A M, Kosynkin V D, Yakimov M Yu 1986 Combustion Explosion and Shock Waves 22(2) 214
[9] Kuznetsov V.A., Solovyov N.G., Shemyakin A.N., et al. 2013 Proc. SPIE, 8600, 860002. doi:10.1117/12.2003658
[10] Baranowski A, Mucha Z, Peradzynski Z 1977 Bulletin de l’Academie Polonaise des Sciences 25(4) 361
[11] Makhviladze G M, Selezneva I K 1981 Journal of Applied Mechanics and Technical Physics 22(5) 646
[12] Cetegen B. M., Ahmed T. A. 1993 Combustion and Flame 93 157
[13] Xia Xi, Zhang Peng 2018 Journal of Fluid Mechanics 855 1156–69 https://doi.org/10.1017/jfm.2018.707
[14] Boettcher P, Menon S, Ventura B, Blanquart G, Shepherd J 2013 Journal of Fluid Mechanics 735 176 doi:10.1017/jfm.2013.495
[15] ANSYS CFX http://www.ansys.com/Products/Fluids/ANSYS-CFX (reference date 20.02.2020)
[16] Raizer Yu P, Surzhikov S T 1989 Fluid Dynamics 24(4) 593
[17] Murphy A.B., Tam E. 2014 J. Phys. D: Appl. Phys. 47 295202 https://doi.org/10.1088/0022-3727/47/29/295202