Buoyancy driven convection instability and related pulsing of continuous optical discharges

S Yu Lavrentyev, N G Solovyov, A N Shemyakin, M Yu Yakimov
Ishlinsky Institute for Problems in Mechanics RAS
101-1, prospect Vernadskogo, Moscow, 119526, Russia

yakimov@lantanlaser.ru

Abstract. Optical discharges find now ever expanding applications in science, engineering and medicine. In present study authors discuss the phenomenon of periodic pulsing of a continuous optical discharge (COD) on the base of original experimental results. In the literature there is no general agreement regarding the origin of the considered instability. Authors have obtained the dependence of oscillation frequency on the gas pressure and proposed semi-empirical relations to estimate pulse frequency pressure dependence observed. Regular self-sustained oscillations of COD plasma were explained by the pulsations of heated gas bubble surrounding COD followed by buoyancy driven vortex formation that was detected on schlieren images of convection zone. This kind of buoyant convection instability was determined to obey the same similarity law as cycling frequency of puffing or flickering in diffusion and premixed flames. The instability discussed can affect the performance of COD in some important applications such as high brightness broadband light sources, for instance.

1. Introduction
Optical discharges are now widely used for generation and sustaining high temperature plasma of high energy dissipation density in various technical and scientific applications [1-6, 14]. One of the most important features of the optical discharges is outstanding stability of plasma characteristics provided by high stability of supporting laser radiation, together with possibility of sustaining microplasma with high energy dissipation density with size and shape easily controlled by means of focusing optics. All these attractive features may be realized in small scale in portable laboratory equipment. Optical discharges may be initiated and sustained by continuous-wave or periodic-pulse laser radiation of various wavelengths in medium or near infrared bands. Due to plasma transparency for certain spectral bands optical discharge characteristics depending on gas type, pressure and temperature may be easily monitored by spectral optical probes.

Under certain conditions essential for some applications optical discharge plasmas exhibit instability. Just in pioneer experiments on obtaining COD self-excited oscillations were observed related to thermal gravity (buoyancy induced) convection instability [7]. Pulsations of thermally induced convective plume exhibit their selves together with regular oscillations of brightness and spatial location of COD plasmas that make difficult their application as stable high brightness radiation source. Special tricks should be applied to overcome this drawback that may be difficult to attain [5].
There is no general agreement regarding the nature of the considered instability in the literature [8-12] that make further obstacles to suppress it effectively. Authors have obtained the dependence of the oscillation frequency on the gas pressure and proposed general relations to estimate pulse frequency dependence observed given underneath.

The essential feature required of gaining acceptance recently high brightness radiation sources employing COD is exceptional temporal, spatial and spectral stability of their broadband radiation. Thus the problem of COD pulsing revealed in [7] and further studied in [8-12] remains the issue of current interest.

2. Experimental set-up and results
In this work authors have investigated processes manifested their selves first in a form of relatively low amplitude (less than 1% in general) pulsations of plasma brightness of COD sustained in the experimental model of broadband high-brightness light source LPS-50 (figure 1) [14], for instance.

In LPS-50 light emitting plasma is sustained in quartz bulb filled with high pressure xenon due to absorption of the radiation of two diode lasers emitting radiation at $\lambda = 0.97 \mu m$ each at full continuous power of 25-30 W (total rated power $P_l = 2 \times 26 W$). Two laser beams each focused with f-number $f/3.5$ were arranged to cross near the beam waists at the angle 60° forming a location of the discharge zone. Plasma was sustained by both beams in the intersection volume about 170 μm long and 100 μm wide. To eliminate obvious sources of plasma pulsations laser radiation was carefully stabilized, diode operating temperature was fixed by means of Peltier thermo-elements, all possible vibrations of the construction elements and optical fibers induced by cooling fans were excluded.

![Figure 1](image)

**Figure 1.** Photo (a) and central cross section scheme (b) of the lighthouse of laser plasma broadband light source LPS-50. 1 – fiber laser beam feed coupled to collimating and focusing lenses; 2 – high pressure xenon quartz bulb; 3 – laser beam stop.

In spite of all the precautions pulsations of COD brightness were observed at different xenon pressures ($p_{Xe} = 15; 30; 40$ bar), set in specially prepared different quartz discharge bulbs. Data were obtained in steady-state conditions when the gas pressure were increased and stabilized after heating by the discharge in a closed volume of the bulb. Pulsations of the brightness in the central region of COD plasma were registered by photomultiplier (PMT) operated in linear response regime. Small portion of plasma radiation was directed to the PMT with achromatic lens that built magnified ($\times20$) image of plasma at the PMT input diaphragm of less than 0.5 mm in diameter. Signal was registered by means of digital oscilloscope and then subjected to Fourier transform to obtain frequency spectrum of the oscillations.
Figure 2. a) Typical time diagram of brightness pulsing for COD sustained in high pressure xenon in two focused laser beams crossing ($\lambda = 0.97 \mu m$, $P_l = 2 \times 26 W$, f/3.5, $p_{Xe} = 15$ bar); b) frequency spectra of COD plasma brightness pulsations, obtained at different actual xenon pressures $p_{Xe} = 15, 30, 40$ bar (correspondingly from the left peak to the right: blue, red and green curves).

Figure 2, a) shows sample oscillogram of pulsations of thermal radiation taken for COD in Xe at 15 bar. Figure 2, b) depicts pulsation spectra obtained with fast Fourier transform applied to the oscillograms corresponding to different current gas pressures in the discharge bulbs.

It was found that main pulsation frequency is increased with pressure but weakly depends on laser power dissipated in plasma, whereas laser power absorbed in plasma was declined up to several times while laser power was approaching down to a threshold value of COD sustaining.

The result obtained is mainly in agreement with the data reported in [12] for COD sustained by CO$_2$ laser in different ranges of gas pressure and plasma characteristics. Discussions on the results and physical model of instability observed presented in [12] cannot be accepted correct, as it was shown in [11]. Possible mechanism of COD plasma oscillations, elaborated in [8], ignores laser beam refraction in plasma and is in contradiction with the results of one-dimensional laser combustion wave stability analysis, consistently performed in [11].

Supposing that real reason of plasma instability is nonstationary convection flow around the plasma, author has employed high-speed filming of the dynamics of gas density gradients around COD visualized by schlieren method (Figure 3).

Figure 3. Schlieren imaging scheme. 1 – LPS-50 lighthouse cross-section; 2 – high pressure xenon quartz bulb with plasma; 3 – back reflecting spherical mirror; 4 – achronatic lens objective; 5 – vertical slit diaphragm; 6 – horizontal slit diaphragm; 7 – fine grain rear projection screen; 8 – camera.
Shlieren patterns were obtained using COD plasma itself as a point source. Plasma radiation was partially collected by spherical mirror and reflected back to pass through the discharge zone. The image of the vicinity of the plasma in passed through light was created by lens objective on the fine grain rear projection screen used for filming. Light passed through the discharge zone inside thick wall quartz bulb becomes astigmatic and forms two separate line foci past the objective. Two slits were used to transmit passed through reflected light and suppressing direct light from COD. The same slits were used to obtain dark-field schlieren image. Direct light was also presented on the images by correspondent vertical and horizontal line patches and dimmed plasma image itself.

Figure 4 shows the frames obtained at xenon pressure 20-25 bar. On the presented frames and high-speed (up to 800 fps) film itself one may observe sequential stages of growing hot gas bubble around COD and strictly periodical buoyancy driven upward motion of the bubbles.

White line indicating maximum refraction index gradient represents the boundary between gas, directly heated from plasma (about 3 kK) and colder (up to 500 K) ambient gas (inside the quartz bulb). Ambient gas temperature inside the bulb is close to the temperature of the built-in electrodes that was measured by IR pyrometer. Current xenon pressure inside the bulb could be derived from known cold bulb pressure being inversely proportional to the temperature. The value of current pressure could be also independently controlled by measuring threshold laser power required to sustain COD [13]. Hot gas temperature on the boundary of the hot gas bubble observed was estimated from the refraction index temperature dependence of high pressure xenon.
Bottom front of a heated gas bubble around COD was found to be semispherical growing from minimal radius $r_0 = 0.65\, \text{mm}$ almost two times up to $2r_0 = 1.3\, \text{mm}$ during about $15\, \text{ms}$. Growing bubble starts floating up due to buoyancy force and acquires the speed of natural convection. All phases repeat with period $23\, \text{ms}$ corresponding pulse frequency $44\, \text{Hz}$, equal to oscillation frequency of discharge brightness at the same gas pressure.

3. Discussions on the results

Some qualitative speculations and quantitative estimations should be made to provide theoretical ground for the effect observed. Simple physical model was proposed for rough quantitative estimations.

In LPS-50 light emitting plasma is sustained in quartz bulb filled with high pressure xenon due to absorption of the radiation of two diode lasers in the location of intersecting their focused beams of total laser power $P_l = 2\times26\, \text{W}$. The expansion of heated gas volume around plasma was obviously produced by thermal component of the energy dissipation in plasma. In typical experimental conditions when incident laser power was 1.5-2 times larger than the plasma sustaining threshold level, plasma absorbed about 50% of the incident laser power. About 50% of the absorbed laser power was reradiated by the plasma in the form of thermal radiation, the rest may be treated as thermal component of plasma energy losses.

At given value of dissipated power thermal component $Q$ the expansion of the heated gas volume will slow down as the front radius $r$ is increased. Simple estimation formula for hot gas bubble expansion velocity $V_t(r)$ could be derived from simplified energy budget. The formula expresses the idea that all thermal energy released is transmitted to the bottom hemisphere front of the bubble (upper front is obviously absent when convective flow is established).

$$V_t(r) = \frac{QM}{2\pi Cp \rho(T) (T-T_1)}, \quad (1)$$

where $M$ is $\text{Xe}$ atomic mass in unified atomic mass units, $C_p$ - $\text{Xe}$ heat capacity, $\rho(T_1)$ - $\text{Xe}$ volumetric mass density at ambient temperature $T_1$, $T$ – average hot gas temperature on the bubble front. In this consideration specific physical mechanism of heat transmission – heat conductivity or convection – were not included. In real both mechanisms contribute to the result, but in this simplified consideration we implicitly suppose that the heat is transmitted instantaneously.

![Figure 5](image)

**Figure 5.** Near-COD heated gas bubble expansion velocity $V_t(r)$ and the bubble floating up velocity $V_c(r)$ plotted against the bubble radius $r$. Pulsing range (shadowed) from minimum radius $r_0$ up to maximum radius $2r_0$ of floating up bubble. Calculation performed for $Q = 10\, \text{W}$, $T_1 = 400\, \text{K}$, $T = 3\, \text{kK}$, $p_{\text{Xe}} = 20\, \text{bar}$.
Buoyant floating up of the hot gas bubble will oppositely tend to accelerate with radius accordingly to well known formula $V_c(r) = \sqrt{2rg}$, where $g$ is gravity acceleration. The formula may be easily derived from the balance of the drag and buoyant forces of the floating up bubble.

Thermal gravity convection may be treated established when bubble front expansion velocity becomes equal to the floating up velocity. The last condition means that the value of front radius of a steady convection would depend weakly on the other parameters.

Figure 5 shows both dependencies $V_t$ and $V_c$ plotted against the bubble radius $r$. Parameters used for this calculation correspond to that of used to obtain data presented in figures 2, 4. Intersection point of the curves gives the value $r_0$ of the expanding front of the bubble stabilized by buoyant convection. As one can see value $r_0$ corresponds to minimal radius of thermal expansion front presented in figure 4, a). Maximum radius of the floating up heated gas volume roughly equals $2r_0$, as in figure 2, c).

Shadowed range between $r_0$ and $2r_0$ correspond to variations of thermal front radius, bubble expansion velocity and buoyant convection velocity during the period of pulsation. The bubble radius is increased from $r_0$ to $2r_0$ during bubble floating up stage. Bubble expanding velocity is decreased as the radius is increased. Estimation formula may be derived for the pulsation frequency $f$:

$$v = \frac{V_t(2r_0)}{r_0}.$$  \hspace{1cm} (2)

Calculations with the parameters indicated in Figure 5 caption (except for gas pressure) give for $p_{\text{Ne}} = 15; 30; 40$ bar correspondingly $v_{15} = 41$ Hz, $v_{30} = 47$ Hz, $v_{40} = 50$ Hz, being close to experimentally observed pulsation frequencies, correspondingly 40, 47 and 53 Hz.

Thus the emerging picture of the observed plasma brightness oscillations related to the instability of buoyant convection area around COD seems to be as follows. Starting from establishing steady radius of heated gas front stabilized by buoyant convection, the heated gas volume continues growing upward and sideward due to intense vortex convection inside the heated gas bubble from its axis to the periphery. The vorticity of the gas motion manifests itself at a certain stage of the pulsation period when cold ambient gas drawn by the vortex into the convective flow forms additional density gradient surface clearly seen on the schlieren patterns (figure 4, b). As the bubble is growing the floating up velocity is increased and the bubble is periodically risen up out of the COD area inducing buoyant driven pulsations in the ambient gas and plasma. Semi-empirical model based on this physical representation gives oscillation frequency estimation close to the observed ones.

Formula (2) may be reduced to the form well known from theory and practice of diffusion and premixed puffing or flickering flames [15-17]:

$$v = \frac{1}{2} \left( \frac{g}{2r_0} \right)^{\frac{1}{2}}.$$  \hspace{1cm} (3)

Replacing $2r_0$ in (3) by $D$, where $D$ means burner diameter or flame diameter, one will get similarity law for pulsation frequencies of flames widely discussed in [15-17] and many other papers on the base of the results of numerous experiments covering wide range of flame sizes and pulsation frequencies. Thus COD also follows the same similarity law, but differs from the case of the flames by considerably higher realization pressures and by correspondingly higher pulsation frequencies and smaller diameters of the buoyant convective flow.

4. Summary and conclusion

Based on original experimental results authors of the present study performed the analysis of spatial and temporal effects occurred as manifestation of buoyant convection instability in the unusual case of very concentrated heat source that can be produced by optical discharges in gases under very high pressures. Simple semi-empirical consideration used employs rough physical model that gives some quantitative estimations of the effect of the considered instability on COD plasma characteristics.
In fact buoyant convection instability around concentrated thermal source produces self-sustaining oscillations of the convection flow that also affect brightness and position of high temperature plasma core of COD. Rough physical model permits to derive formula for oscillation frequency dependence on pressure that is in agreement with the experimental results obtained. It was shown that the formula is reduced to the form coinciding with similarity law for puffing and flickering flames, well-known from many experiments and computer simulations. Data derived from experiments with optical discharges will extend the range of workability of the similarity law up to higher pressures and higher oscillation frequencies.

Periodical oscillations of plasma brightness of COD induced by buoyancy driven pulsations play negative role in some important applications, affecting the stability of broadband high brightness light sources, for instance.

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