“Electrical wind” in CO₂-laser mixtures at superatmospheric pressures

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Abstract. This article presents the results of "electrical wind" investigations in CO₂–laser mixtures at superatmospheric (1–12 atm) pressures. It is established that for a fixed value of the unipolar corona discharge current, the gas flow velocity does not depend on the pressure, but is determined by the chemical composition of the working mixture. The maximum values of the "electrical wind" velocity are achieved in carbon dioxide and molecular nitrogen and their values are 3.2 and 2.9 m·s⁻¹. In typical laser mixtures CO₂:N₂:He = 1:1:1 – 1:1:3 the velocity of the "electrical wind" are in the range from 2.5 to 1.5 m·s⁻¹.

1. Introduction
"Electrical wind" is a unique method of transverse pumping of gas mixtures through a gas-discharge gap in small–sized sealed–off CO₂–lasers at atmospheric and superatmospheric pressures in order to increase the pulse repetition rate. In addition, the need to research the "electrical wind" is dictated by the requirements of the formation of gas flows for electron–ion technologies, ozone generation and the production of gas flows in aggressive and high temperature gas environments [1, 2].

The "electrical wind" is formed using two electrodes for ignition of a unipolar corona discharge and does not have rotating elements in its composition. The electrode structure has a minimum size and weight and has a "vacuum purity". The latter property is extremely important for creating sealed–off versions of TEA–lasers.

The use of the "electrical wind" in small–sized sealed–off TEA–CO₂ lasers made it possible to increase the pulse repetition rate from several Hertz to 20–50 Hertz [2–4].

This work is devoted to the study of the properties of the "electrical wind" in CO₂–laser mixtures at pressures up to 12 atmospheres. The dependences of the "electrical wind" velocity on such parameters as the structure of the electrodes, the size of the interelectrode gap, the corona discharge current and the component composition of the working mixture were investigated. The studied mixtures were consist of carbon dioxide, molecular nitrogen and helium with the component ratios characteristic of sealed–off TEA–CO₂ lasers: CO₂:N₂:He = 1:1:8; 1:1:6; 1:1:4; 1:1:3; 1:1:2; 5:1:3, etc.

The effect of the "electrical wind" is based on the transfer of pulses from ions moving in an electrical field mainly in one direction to chaotically moving atoms and molecules of the working mixture. Unidirectional ion flows are formed in the so-called "unipolar" corona discharges [1]. In this
case, the direction of the gas flow ("electrical wind") is always directed from the corona electrode to the non–corona electrode, regardless of the polarity of the voltage on the corona electrode [1, 2].

The value of the "electrical wind" velocity ($V_{\text{EW}}$) is a very complex function of a great number of electrophysical, geometric and gas parameters [1–5]. The limit value of the "electrical wind" velocity can be estimated on the basis of the law of conservation of energy. To solve this problem, it is necessary to introduce a number of assumptions [3]:

- the electric field in the discharge gap is assumed to be homogeneous;
- there is no viscous friction;
- all the kinetic energy of the ion flow as a result of collisions between ions and neutral atoms and molecules is completely transferred to neutral atoms and molecules of the gas mixture.

Under these conditions, the maximum value of the "electrical wind" speed is determined by the ratio:

$$V_{\text{EW}} = \sqrt{\frac{2 \cdot j \cdot d}{\rho \cdot \mu}},$$

where $j$ is the current density of the corona discharge, $d$ is the value of the interelectrode gap, $\rho$ and $\mu$ are the density of the gas and the mobility of the ions.

The value ($\rho \cdot \mu$), as is known [6], does not depend on the pressure and is a constant value. Its value for the air is $\approx 2.5 \cdot 10^{-4}$ kg·m⁻¹·V⁻¹·s⁻¹. For typical corona discharge current densities $j \approx 10^{-4}$ A·m⁻², the maximum value of the "electrical wind" velocity is $\approx 30$ m·s⁻¹. This value is the limit, above which the velocity value cannot be. The maximum values of the "electrical wind" velocities measured experimentally for atmospheric air are in the range of 5–8 m·s⁻¹ [1, 2, 5].

As studies of the electrical characteristics of the corona discharge have shown the magnitude of the corona discharge current increases with increasing pressure. In this regard, in accordance with expression (1), we should expect an increase in the speed of the "electrical wind" with an increase in the pressure of the active medium of the gas–discharge laser.

2. Experimental part

2.1. Experimental equipment and method of the "electrical wind" velocity measuring

The structural scheme of the experimental equipment is shown in figure 1. The corona (2) and non-crowning (3) electrodes are located in the working container (1) made of stainless steel. The non-crowning electrode is made of a metal grid (Ni, W). The "electrical wind", which is formed in the gap between the electrodes (2) and (3), penetrates through the grid electrode and the gas flow inside the container encloses as shown by the arrows in figure 1.

![Figure 1. General scheme of the experimental equipment.](image-url)
In this work, a Prandtl velocity sensor (VS) was used instead of the small–sized thermistors previously used for conducting studies at full pressure in one atmosphere [2, 3]. The transition from the thermoelectric to the gas–dynamic method of measuring the velocities of gas flows was due to the fact that in the latter case there is no need for complex and lengthy calibration operations of the thermistor for each of the studied gas mixtures. In addition, the Prandtl method is easily applicable for superatmospheric pressures. The velocity sensor (dynamic pressure meter) is located behind the grid electrode.

In the Prandtl sensor, the absolute value of the gas flow velocity is directly related to the value of the dynamic pressure. A U–shaped pressure gauge (U–M) is used to measure this value. One arm of this pressure gauge is connected to a tube installed towards the gas flow, and the second to a tube located in close proximity to the first, but oriented perpendicular to the flow. The pressure drop (the difference between the total pressure and the static pressure) is the dynamic pressure $P_{\text{DYN}}$ and it is directly recorded by a U–shaped pressure gauge. The value of this pressure is related to the gas velocity in the vicinity of the receiving tubes by the ratio [7, 8]:

$$ P_{\text{DYN}} = \frac{\rho \cdot v^2}{2}. \tag{2} $$

Based on this ratio, the "electrical wind" velocity is experimentally determined as:

$$ V_{\text{EW}} = 2 \cdot \frac{P_{\text{DYN}}}{\rho_{\text{GAS}}} = \sqrt{\frac{2 \cdot \rho_{\text{LIQ}} \cdot g \cdot \Delta H}{\rho_{\text{GAS}}}}, \tag{3} $$

where $\rho_{\text{LIQ}}$ is the density of the liquid (VM–1 vacuum oil) in a U–shaped pressure gauge, $\rho_{\text{GAS}}$ – gas density, $g$ – acceleration of free fall, $\Delta H$ is the pressure drop in the U–shaped pressure gauge.

Gas discharge chamber (1) (figure 1) before filling it with the studied mixtures $\text{CO}_2$:$\text{N}_2$:$\text{He}$ in the required proportions is pumped out by a pre–vacuum pump (FVP) to a residual pressure of $10^{-2}$ Torr. After that, with the help of a system of vacuum valves $K_1$–$K_4$, the gas discharge chamber is filled with the studied gases with the necessary component composition in the pressure range from 1 to 12 atmospheres. The pressure in the discharge chamber was monitored using a pointer pressure gauge (M). Industrial purity gases were used during the research.

The corona discharge was ignited from a regulated high voltage source ($U_0 = \text{Var}$). The value of the voltage at the source could be smoothly adjusted in the range from 0 to 60 kV with a maximum discharge current of up to 10 mA. If necessary, the voltage polarity could be reversed. The voltage at the gas–discharge gap and the corona discharge current were measured using a static kilovoltmeter C–96 (kV) and arrow micro– and milliamperimeters (mA).

Threads, blades, and needles were used as corona electrodes. Non–corona electrodes were made of twisted wire meshes made of nickel and tungsten meshes. The latter were made by laser burning holes technologies. Tungsten grids were used at currents of more than 0.5 mA. The transparency of the grid electrodes in relation to gas flows reached 60%. In a number of experiments, electrode structures were used without the use of grids. These were cylindrical rings and extended cylinders. The latest versions of electrode structures for the formation of an "electrical wind" do not ensure the necessary stability of the gas flow velocity and they were not used in the active elements of TEA–$\text{CO}_2$ lasers.

The discharge chamber and all pipelines were designed for a pressure of up to 25 atmospheres. For visual observations of the spatial structure of corona discharges, an observation window was provided, which was closed by a quartz plate with a diameter of 40 mm and a thickness of 10 mm.

2.2. Results of experimental investigations

2.2.1. "Electrical wind" at pressures in 1 atmosphere. Figure 2 shows the characteristic dependences of the "electrical wind" velocity on the corona discharge current for the positive (curves 1, 3, 4) and
negative polarities of the voltage at the corona electrode (curves 2, 5). The "thread–grid" variant was used as the electrode system. The thread diameter was 0.2 mm. Both electrodes were made of nickel. The size of the interelectrode gap was 1 cm. The maximum values of the corona discharge currents correspond to the corona discharge transition into the spark discharge.

\[
V_{EV}, \text{m} \cdot \text{c}^{-1}
\]

![Figure 2](image)

The relatively narrow range of current values for the positive polarity of the voltage at the corona electrode is in the range 0.05–0.2 mA. For a negative polarity of the voltage on the corona electrode the maximum values of the currents reach 0.5–0.6 mA.

The values of the "electrical wind" velocity strongly depend on the concentration of helium in the working mixtures and the polarity of the voltage at the corona electrode. At significant concentrations of helium in mixtures CO\textsubscript{2}:N\textsubscript{2}:He (up to 80%) the velocities of the "electrical wind" are 0.6–0.8 m·s\textsuperscript{-1}. In mixtures CO\textsubscript{2}:N\textsubscript{2}:He = 1:1:2–1:1:1, in which the laser radiation energy has maximum values, the "electrical wind" velocities reach 3.5–4.0 m·s\textsuperscript{-1}. When filling the gas–discharge chamber with atmospheric air, the velocities of the "electrical wind" reach values of 5–6 m·s\textsuperscript{-1}.

The dependences presented in figure 2 indicate the expediency of using a "negative" corona due to a larger range of operating currents, greater resistance to degeneration into spark channels with the subsequent disappearance of the "electrical wind" effect and some excess of the maximum velocity values over the corresponding values characteristic of a "positive" corona.

The use of "electrical wind" for the purposes of convective renewal of gas mixtures in the gas–discharge gaps of small–sized sealed–off TEA–CO\textsubscript{2} lasers ensures the achievement of maximum pulse repetition frequencies of the order of [9]:

\[
F_{\text{MAX}} = \frac{V_{EW}}{(2-5) \cdot \Delta},
\]

where \(V_{EW}\) — "electrical wind" velocity in the discharge gap, in which ignited the volume discharge; \(\Delta\) is the width of the electrodes for ignition volume discharge along of flow; multiplier (2–5) before the value \(\Delta\) reflects the slow updates convective gas mixtures in the near–electrode regions.

For typical values of the width of the electrodes for ignition of a volume discharge along the flow \(\Delta = 1\) cm and the "electrical wind" velocities \(V_{EW} = 3.5–3.7\) m·s\textsuperscript{-1}, expression (4) gives for the maximum values of the pulse repetition frequency in small–sized sealed–off TEA–CO\textsubscript{2} lasers up to 50–70 Hz. These values are an order of magnitude higher than the characteristic values of the pulse repetition frequency in TEA–CO\textsubscript{2} lasers with a diffusion regeneration of the working mixtures in main discharge gap.

2.2.2. "Electrical wind" at pressures up to 12 atmospheres. For determining the capabilities of a corona discharge for the formation of directed gas flows, it is important to know its volt–ampere characteristics at different pressures and component compositions of gas mixtures. Figure 3 shows...
The investigations were carried out in the "pins–grid" electrode structure with an interelectrode gap of 4 mm. The corona discharge breakdown increase with increasing pressure almost linearly. The maximum values of corona discharge currents that can be achieved in the studied gas mixtures decrease with increasing pressure. The values of the corona discharge currents are limited by its degeneration into a spark channel. Under these conditions, the "electrical wind" disappears. For the full pressure of the gas mixture CO₂:N₂:He = 1:1:2 in 1 atmosphere, the maximum value of the corona discharge current reaches 900 µA at a voltage over a 4.5 kV. At a pressure of 12 atmospheres, the maximum current value of 200 µA is reached at a voltage at a range of 30 kV.

With an increase in the concentration of helium in working mixtures (CO₂:N₂:He = 1:1:4–1:1:8) the values of the corona discharge currents increase. Along with this, the voltage range of a stable corona discharge also increases. In mixtures CO₂:N₂:He = 1:1:4–1:1:6 the current value of 1000 µA is achieved at voltages less than 4 kV.

The behavior of the "electrical wind" velocities as a function of pressure for a fixed value of the corona discharge current in carbon dioxide (1), molecular nitrogen (2) and a mixture of CO₂:N₂:He = 1:1:4 is shown in figure 4.

The values of the "electrical wind" velocity for a fixed value of the corona discharge current are almost independent of the pressure value. The obtained results are in accordance with the expression (1), according to which for fixed values of the discharge current and the size of the discharge gap, the value of the "electrical wind" velocity does not depend on the pressure, since the multiplication of the gas density on the mobility of ions is a constant value.

The "electrical wind" velocity for all three gas compositions presented in figure 4 changes very slightly with increasing pressure. The maximum values of the velocity ≈ 3 m·s⁻¹ are characteristic of pure carbon dioxide. The reason for this is the largest mass of ions that are formed in the corona discharge, and have a more efficient transfer of momentum in collisions with neutral molecules.
Reduction of the velocity value in mixtures CO$_2$:N$_2$:He is due to the presence of a noticeable number of helium atoms in the mixture, which are less effective in terms of momentum transfer in collisions with neutral atoms and molecules. In pure helium, the speed of the "electrical wind" is only $\approx 1 \, \text{m/s}$. As it was shown earlier, the values of the "electrical wind" velocities of 2–3 $\text{m/s}$ are sufficient for the formation of a volume discharge in the interelectrode gap with the width of the electrodes along the flow of 1 cm at pulse repetition frequencies of several tens of Hertz. The "electrical wind" effect is widely used in laser technology when creating small–sized sealed–off TEA–CO$_2$ lasers. The same effect can be successfully applied in the development of small–sized sealed–off CO$_2$ lasers operating at superatmospheric pressures.

2.2.3. Application of "electrical wind" in small–sized sealed–off TEA– and TE–CO$_2$ lasers. The formation of "electrical wind" inside the active elements of small–sized sealed–off CO$_2$ lasers at superatmospheric pressure is carried out by the same means as at atmospheric pressure. Metals and ceramics are used as the outer shell of the active elements of super–atmospheric pressure CO$_2$ lasers. Operation at pulse repetition frequencies of several tens of Hertz leads to a noticeable heat generation inside the active element and heating of the working gas mixture. In order to remove heat from the active element small–sized water–cooled heat exchangers are used. The relative position of the main and auxiliary electrodes inside the active element is shown in figure 5.

![Figure 5. Mutual arrangement of the main components inside the active element of the TE–CO$_2$ laser.](image)

Inside the ceramic shell (1) there are main electrodes (A–C) for igniting a volume discharge and pumping the active medium, electrodes for pre–ionization of gases (PE) in the main discharge gap and another pair of corona electrodes (CE) and non–corona (NCE) electrodes. High–voltage pulses for the excitation of volume ($-U_{VD}$) and auxiliary ($-U_{PD}$) discharges can be applied to the corresponding electrodes from either one or two autonomous generators. In the latter case, the moments of turning on the generators are strictly synchronized in time. Corona discharge for the formation of "electrical wind" is ignited from an autonomous current source ($-U_{CD}$).

The "electrical wind" circulating inside the active element, in addition to convective renewal of the gas medium in the interelectrode gap in the pause between pulses, blows gas through the plates of the water–cooled heat exchanger (HE). The presence of a heat exchanger stabilizes the value of the laser radiation energy in the pulse in magnitude and eliminates its noticeable decline over time.

Investigate of the energy parameters of TE–CO$_2$ lasers on mixtures CO$_2$:N$_2$:He = 1:1:4–1:1:6 it was shown that the value of the radiation energy in a pulse at a pulse repetition frequency of 20 Hz increases linearly with pressure and when the active medium is excited in the volume $V = 18 \times 0.8 \times 0.8 \, \text{cm}^3$ the maximum value of the radiation energy in the pulse reaches 1 J [10].

3. Conclusion
1. For the first time, the basic laws of the "electrical wind" in CO$_2$–laser mixtures at pressures up to 12 atmospheres have been studied. It is established that for a fixed value of the corona discharge current, the value of the "electrical wind" velocity does not depend on the pressure.

2. The volt–ampere characteristics of the corona discharge in the gap indicate a reduction in the range of currents within which the corona discharge does not pass into the spark channel.

3. In CO$_2$–laser mixtures with a ratio of components CO$_2$:N$_2$:He = 1:1:1 – 1:1:3 at pressures up to 8 atmospheres and a corona discharge currents up to 500 µA achieved speed "electrical wind" to 2.9–3.2 m·s$^{-1}$.

4. At the present time designed some samples of metal–ceramic small–sized sealed–off TE–CO$_2$ lasers working at superatmospheric pressures at the pulse repetition frequencies up to 25 Hz.

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