Influence of mechanical action on the development of
electrodynamic phenomena in ionized gas

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Abstract. A special feature of this work is the study of the effect of mechanical mode
disturbances on the discharge and plasma flow. It is found that the mechanical impact of a
shock wave in a dense gas in an electric field of high intensity almost to the ignition voltage
causes an electrical “breakdown” as current peaks. The ultrasonic effect on the flow of the
reacting plasma of the air as shown by the analytical study of the thin layer of the plasma flow
changes the type of flow.

1. Introduction
Currently a large number of works are devoted to the study of the effects of electrical phenomena such
as discharges on mechanical systems, for example, gas flows [1,2]. The flow becomes turbulent,
which shifts the point of separation and changes the aerodynamic coefficients. In this paper, we study
the effect of the mechanical mode disturbances on the occurrence of discharge and plasma flow. In the
first section we study the effect of a shock wave moving between the electrodes with the applied pre-
“breakdown” voltage on the occurrence of a “breakdown” in the form of a short-term current pulse. In
the second section we develop a method for studying the stability of a narrow layer of a gas flow with
physicochemical reactions and a transverse gradient of the longitudinal velocity. The dissipative
properties of the gas are taken into account. For ionized air mechanical action in the form of
ultrasonic waves causes a change in the type of plasma flow – flow becomes turbulent.

2. Shock wave-initiated discharge

2.1. Results in the air
The occurrence of “breakdown” behind the shock wave which appear as current peaks figure 1 looks
strange since in accordance with the Paschen curve an increase in pressure in a dense gas should led to
an increase in the critical “breakdown” voltage. The density growth behind the shock is small.

Although the electric field is inhomogeneous near the cathode but in the center of the discharge the
direction of propagation of the shock wave is perpendicular to the electrical field strength. The
appearance of peaks is chaotic, there may be a repetition of peaks, but on average they appear with a
delay of 150-250 microseconds. So this mechanism is impossible.

The peculiarity of this work is that the mechanical impact of the shock wave is proposed as the
initiator of the “breakdown”. The experiments were carried out on a plasma-gas-dynamic installation
the description and scheme of which are given in [3] at a pressure of 4 kPa and shock wave velocity of
about 1000 m/s and a distance between the electrodes of 10 cm. Applying pre-“breakdown” voltage is
10 % less than the discharge ignition voltage (4.5 kV).

![Figure 1](image1.png)

**Figure 1.** “breakdown” delay after passing through the center of the discharge gap of a shock wave of different speeds: 1-790 m/s, 2-600 m/s, 3-670 m/s. The current in the discharge gap is on the abscissa axis. The voltage at the electrodes is 3.9 kV. 0 – shock wave position.

2.2. Discussion of possible reasons for the appearance of current peaks

The first thing that comes to mind is that "spark" can occur in a gas plug that is saturated with charged particles and metal vapors since the shock wave is initiated by an electric discharge in an electrodynamic shock tube. This reason is impossible because figure 2 clearly shows that the delay is much less than the arrival time of the plug 800 µs.

![Figure 2](image2.png)

**Figure 2.** The signal from the double probe at the same shock wave speed as in figure 1 (790 m/s). 1 – in a cold gas without ignition of the discharge, 2 - in a damped discharge, 3 - in a burning discharge.

A small direct current in the figure 3 is not a current in the discharge gap, although it is also available, but of a lower intensity. It is a consequence of the superimposition of current in the experimental setup for verifying the results.

The next thing that comes to mind is additional ionization through the excitation of electronic states due the temperature growth behind the shock because delay time is consistent with the excitation time. However in experiments in nitrogen which has no low–lying excited states as in air – singlet oxygen the peaks do not disappear figure 3.

Finally the discharge in the installation is not uniform. If the anode has a flat shape then the cathode has a conical shape (the angle at the top of the cone is 120°). It is known that the inhomogeneity of the
Figure 3. “breakdown” in nitrogen after passing through the center of the discharge gap of a shock wave of different velocities: 1‒810 m/s, 2‒650 m/s, 3‒710 m/s.

The voltage at the electrodes is 3.9 kV.

field at the cathode leads to the appearance of a cloud of excess electrons at the cathode which changes the potential at the cathode and increases the “breakdown” voltage [4]. When the shock wave passes the cloud should deflate due to the Coulomb force between electrons and ions, which exist together with the superimposed pre-“breakdown” voltage. As a result the voltage should decrease and “breakdown” should occur. Interacting of shock wave with electrode is not stable what explains the randomness of the appearance of current peaks and the appearance of additional peaks (figure 1,3). Testing this mechanism involves changing the design but we know that this leads to a radical change in the ignition conditions up to the impossibility of ignition.

3. Theoretical study of the effect of ultrasound on the plasma flow

The second example is the effect of a sound field on the flow of plasma and a chemically reacting gas. This task is important not only for the technical problem of increasing the efficiency of plasma and chemical reactors with aid of sound action [5] but also for the theoretical justification of the critical impact of chemical processes on the flow separation [6].

3.1. Setting the research task

The stability of a thin curved layer in which physical and chemical processes of exothermic and endothermic types occur is analyzed. Instability means an increase in pressure disturbances in form $\delta p = A \exp(by) \exp[i(ax - ct)]$ over time. The initial equations for the perturbation amplitudes are obtained from the equations of two-dimensional gas dynamics after applying the normal mode method for a traveling wave along the flow direction $-x$. The flow is a narrow layer, the stroke denotes the derivative across the flow $-y$. $T' = P' = 0$. $U'$, $M$, $P$, $T$, $\rho$, $dQ/dT$ and $dQ/d\rho$-are considered as constant parameters, $Q$ – the power of mass energy release as a result of reactions. Then the normal mode method applies in $y$ direction. For analysis of two-dimensional stability in previous work [5] it was proposed to investigate the roots of a special fourth-degree polynomial obtained from the equations for the amplitudes of two-dimensional perturbations with respect to $Z = -i\alpha p(U - c)/(yTd_\tau Q)$, $a$, $b$-wave numbers along and across the flow, $c$ – the group velocity of perturbations. When deriving the polynomial the properties of the boundary surface are not taken into account. Only the curvature of the flow and the physical and chemical processes are taken into account. The curvature is described by parameter $U'$.

3.2 Flow instability taking into account dissipative properties

It turned out that instability develops for both exothermic and endothermic processes at a high
perturbation frequency which corresponds to the ultrasonic frequency in the case of air ionization \((f = 8 \text{ kHz})\) [5]: \(\lambda < 1/2\). Value \(\lambda\) is a dimensionless wavelength which is zero if the energy release power is zero. It means that the processes of energy release play a decisive role here. This statement for dimensionless variables is generally accepted because it makes possible to solve the problem in the general case, and for a specific task the frequency and increment easy to find by substituting parameters characteristic for the task how it was done for ionization in the air [5]. The increment of perturbations growth increases with a decrease in the \(\lambda\) but at a zero value of \(\lambda\) there is no instability [5]. The jump is caused by the lack of dissipative properties of the medium. Taking them into account gives an equation of the fourth degree:

\[
\begin{align*}
\lambda^2 Z^4 + \lambda^2 Z^3 \left(1 - ibD_0\right) + Z^2 \left(1 - ibV - D\right) + Z \left(g + q \left(1 - ibV\right)\right) + gq &= 0 \\
\lambda &= \bar{\lambda} M \left(\gamma Td_T Q\right) \left(c \rho\right)^{-1} \\
\bar{\lambda} &= \left(a^2 + b^2\right)^{-1} \\
V &= ab \left(a^2 + b^2\right)^{-1} \left(Td_T Q\right)^2 f_0^2 \left(\pi_0 \gamma \text{Re}\right)^{-1} \\
D &= Td_T \gamma - 1 \eta M^2 Uf_0^2 \left(\pi_0 \gamma \text{Re}\right)^{-1} \\
g &= 2U'ab \left(a^2 + b^2\right)^{-1} \left(Td_T Q\right)^{-1} \rho \\
q &= (1 - d) \gamma^{-1} \\
d &= \rho d \rho Q (Td_T Q)^{-1} \\
D &= Td_T \gamma - 1 U'ab \left(a^2 + b^2\right)^{-1} \eta M \rho \left(\gamma \text{Re}\right)^{-1}
\end{align*}
\]

\(\eta\) — dynamic viscosity, \(\text{Re}\) — Reynolds number calculated from the length of the flow section along \(x\), \(f_0, \pi_0\) — amplitudes of two-dimensional perturbations of longitudinal velocity and pressure. Figure 4 shows that with an increase in the dissipative term in the energy equation (dimensionless parameter \(D\)), the increment of the increase in perturbations decreases, that is, the assumptions adopted in the study do not miss the basic physical principles. For values \(D > 1\) when the coefficient at \(Z^2\) if \(V = 0\) becomes negative \(\text{Im} Z\) has a maximum. That is, there is no jump near the zero value of \(\lambda\). At the same time, at small values of the wavelength \((\lambda = 0.1)\), a noticeable increase (three times) in the increment of perturbations is observed for example at \(D = 1.04, 1.06\). This indicates the instability of the flow at the specified parameters. There is no drop in \(\text{Im} Z\) to zero at \(\lambda = 0\) in the calculations for \(D = 1\) and 1.02. Apparently for all values of \(D\) there is a drop to zero. Analytical researches are needed.

**Figure 4.** Decrease in the increment of the increase of perturbations when taking into account the dissipative term associated with the gas viscosity in the energy equation (parameter \(D\)):

1–\(D = 0.99\), 2–\(D = 1.00\), 3–\(D = 1.02\), 4–\(D = 1.04\), 5–\(D = 1.06\). \(D_0 = 1\).
4. Conclusion

Thus, mechanical action under certain conditions can change the flow of the plasma or cause a change in the conditions at the “breakdown” gap.

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