Cascade volumetric acceleration of electrohydrodynamic flows

I E Rebrov
Institute for Electrophysics and Electric Power RAS, 18 Dvortsovaya Promenade, Saint Petersburg, 191186, Russia
E-mail: rbrv.igor@gmail.com

Abstract. Method of cascade volumetric acceleration of electrohydrodynamic flows at atmospheric pressure air using high-voltage rectangular pulse generator was developed and investigated. The charged particles generated by dielectric barrier or corona discharge and accelerated by synchronizing the ion cloud movement with electric field change of the accelerating electrodes. To implement synchronous switching, a two-channel high-voltage square wave generator was used. It consists of 4 high-voltage switches combined in pairs in a half-bridge circuit and operates at frequency from 100 Hz to 100 kHz and voltage of up to 10 kV. Due to the controlled turning on and off of the switches, the minimum duration of high-voltage pulses is less than 200 ns. The generator is loaded with a two-phase multistage volumetric acceleration system of ion clouds.

1. Introduction
Methods of obtaining and accelerating electrohydrodynamic flows in atmospheric pressure air are actively used in pumping and cooling systems, modification of the boundary layer in aerodynamic surfaces, in aircraft with a fully solid-state propulsion [1–3].

The proposed design of ion acceleration and drift section consists of parallel metal grid electrodes connected to the high-voltage generator channels with phase shift to provide longer ion drift distance by asynchronous switching of the electric field. The generation of charged particles is carried out by a pulsed corona or dielectric barrier discharge, then they are injected into the acceleration region. The ion drift velocity in an external electric field can be found as:

\[ \vec{v}_{\text{ion}} = \mu \cdot \vec{E} \]

where \( \mu = 3 \times 10^{-4} \, \text{m}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1} \) – the mobility of nitrogen and oxygen ions in air at atmospheric pressure; \( E \) is the electric field strength not exceeding the breakdown field. At \( E = 10^6 \, \text{V} \cdot \text{m}^{-1} \), the ion drift velocity is 300 m·s⁻¹. Thus, when the distance between the electrodes is 10 mm and, the switching frequency \( f \) will be 33.3 kHz. However, in the process of optimizing the device design, it is necessary to vary the interelectrode gap and, accordingly, the frequency and duty cycle. In addition, for ease of controlling the ions by the traveling field, it is necessary to create a constant accelerating potential difference between the electrodes, which is easily achieved by a rectangular pulse shape with an arbitrary duty cycle. For this purpose, an experimental setup in corona triode configuration [4] and a high-voltage generator are implemented. The general block diagram of a pulse generator and an acceleration system for weakly ionized gaseous media, as well as a measuring instruments for
currents, voltages and speed characteristics of electrohydrodynamic flow, is presented in figure 1. It consists of two grid EHD cascade $C_1$, $C_2$ with optical transparency of 0.83 [5], high-voltage power supply (HPS), plasma emitters (PE), high-voltage switches with drivers (HVS) that forms rectangular pulses [6].

2. System of volumetric acceleration of weakly ionized gaseous media
Spellman SL2000 high-voltage power supply is connected through a current-limiting resistor $R$ with a nominal value of 100 kΩ to plasma emitters and to the high-voltage switches (Sw11, Sw12). HPS voltage can be smoothly varied from 0 to 8 kV and controlled through a high voltage probe using a multimeter $V$. The registration system includes two high-voltage Tektronix 6015A probes, oscilloscope Le Croy Wave Runner 104Xi-A (1 GHz, 10 GS/s), anemometer on two-coordinate positioning system for output electrohydrodynamic flow control. The discharge current was measured by an $A_1$ microammeter, and output current by $A_2$. The number of emitters was selected on the basis of the range and sensitivity of $A_1$ and $A_2$ (10–100 $\mu$A).

![Figure 1. Experimental setup to study the volumetric acceleration of EHD flows.](image)

Each generator channel (HVS$_1$ and HVS$_2$) consists of two solid-state high-voltage switches (Sw$_1$ and Sw$_2$), connected in a half-bridge circuit. HVS are designed for operating voltages over 10 kV and consist of 10 modules of series-connected IGBT without special alignment circuits, which reduces losses when working at high repetition frequencies and will allow opening or closing in less than 200 ns. With forced air cooling of the transistors, operation with a frequency of 100 kHz was achieved. Two synchronized driving generators (DG) provide through the driver (Dr) a full control (turning on and off) HVS and allow you to set the frequency, inter-channel delay and pulse duration. The generator load is the equivalent capacity of stages of the accelerating section. The formation of high-voltage pulses occurs due to the alternate opening and closing Sw$_1$ and Sw$_2$.

The electrical circuit of the switch module is shown in figure 2. The ON signal of the DG generator provides the formation of a positive voltage across the resistor R3. As a result, the gate capacitance is charged through the Schottky diode D1 and turning IGBT transistor Q1 in on-state. When the signal is
OFF (negative pulse), the transistor Q2 through the voltage divider R1, R2 goes into a conducting state, the IGBT gate is discharged and the power transistor turns off.

**Figure 2.** Electrical circuit of one switch module. R1 = 20 $\Omega$, R2 = 10 $\Omega$, R3 = 4.7 $\Omega$, U1 – single turn ferrite transformer, D1 – schottky diode, Q1 – power IGBT 1200V, Q2 – MOSFET 30V, 7A.

In this work the following setup configuration was used: channel 2 remained open, so that a constant high voltage was applied to the PE, $C_2$ was grounded through the resistor R, and $C_1$ was fed by high voltage pulses with a duty cycle $D = \tau / T$, amplitude $U$ and frequency $f$.

The pulse corona discharge was formed at the moment when driver Dr open switch Sw1 and close Sw2. As a result, a high voltage difference arises between the PE and $C_1$. The formation of EHD flow occurs due to the movement of charged particles from the PE to the first collector. After the time $\tau$, the voltage on $C_1$ becomes equal to the voltage on PE, and Every ions start to accelerate in $C_1-C_2$ section.

Microammeters with low pass filter to eliminate the effect of displacement currents during commutation process were used. To make sure that microammeters measure exactly the ion current, the following techniques are applied: replacement of the grid collector $C_1$ with a sheet of foil showed the presence of current $I_1$ through $A_1$ and the absence of $I_2$ (thus, there is no pulse noise); connection of PE and $C_1$ to HVS1 lead to no current through $A_1$ and $A_2$ (there is no plasma generation on PE, and no side discharge processes between two accelerating electrodes $C_1$ and $C_2$).

Graphs of current $I_1$ versus duty cycle $D$ at different frequencies $f$ are shown in figure 3. As can be seen with increasing duty cycle, the current increases linearly. There is also an increase in current with increasing pulse repetition rate at low $D$. At $D = 0.9$ the current becomes weakly dependent on frequency.

By increasing the length of the path by two times (with constant electric field), the work of moving the charge and, consequently, the energy of the EHD flow, doubles. It also does not waste work on regeneration of plasma. It is possible to estimate the corona discharge power for plasma generation $P_d$, according to the inception voltage (or applied voltage) and current. These parameters are strongly influenced by the geometry of the emitter and the receiving collector (in this case, the grid). To reduce the inception voltage threshold, wire with a diameter of 50 $\mu$m was used as PE. Another source of losses in the acceleration circuit is the power that goes from the power source to recharge the capacitor. It can be written with the formula:

$$P_c = f \frac{CU^2}{2}$$

The main contribution to the capacitance is made by the electrodes of the accelerating sections (collectors), which can be considered as parallel plates. The exact value of the capacitance was measured by the slope of the QU characteristic and was 18 pF. The electrical losses due to capacitor
recharging can be reduced by using sinusoidal or sawtooth high voltage waveform or other resonant modes of generator operation.

![Graphs showing the dependence of discharge current on duty ratio and frequency at different voltages.](image)

**Figure 3.** The dependence of the discharge current $I_1$ through the microammeter $A_1$ on the duty ratio and frequency of the signal at different voltages.

As can be seen from figure 4, the grid current transparency $\alpha = I_2/I_1$ at low and medium $D$ varies from 7% at a low frequency and at frequencies above 5 kHz goes to the plateau and reaches 70% at $D = 0.1$ and 30% at $D = 0.5$. At $D = 0.9$ transparency does not depend on $f$ and $U$ and is equal 5±2% and most of the ions di. The plateau frequency is associated with the path of drifting particles:

$$l = \mu \frac{U D}{d f}$$  \hspace{1cm} (3)

If $l$ becomes greater than $d$ or $D$ higher than 0.5, most of the ions are neutralized on the first grid. According to the results of the study for a two-section accelerating module (pulsed corona triode), an ion current at second section through $A_2$ can be achieved of up to 70% of total corona current at a duty cycle of 0.1 and up to 30% at $D = 0.5$. Enhancement of the effectiveness of the EHD flows formation systems is important for creating solid state propulsion aircraft [3, 7] on the base of these devices.
Figure 4. The dependence of $C_1$ current transparency on the voltage and pulse repetition rate for the duty cycle a) $D = 0.1$, b) $D = 0.5$, c) $D = 0.9$.

Acknowledgments
This work was supported by RFBR (grant No. 17-08-01409).

References
[1] Schlitz D J 2004 Ph. D. Microscale ion driven airflow (United States: Indiana Purdue University)
[2] Aleshin B S et al 2017 Technical Physics Letters 43 64
[3] Xu H, Gilmore K, Barrett S R H et al 2018 Nature 563 532
[4] McLean K J, Herceg Z and Boccola R I 1981 Journal of Electrostatics 9 211
[5] Rebrov I E, Khomich V Y and Yamshchikov V A 2016 Tech. Phys. 61 1130
[6] Gamirullin M D et al 2015 Prikladnaya Fizika 5 95 [in Russian]
[7] Khomich V Y and Rebrov I E 2018 Journal of Electrostatics 95 1