Flow visualization around cylinder under surface discharge action in the still atmosphere

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Abstract. The paper presents the universal gas-discharge system for surface discharge generation on a cylinder body providing PIV experiments and shadow studies. The system enables the flow visualization around cylinder, discharge power consumption measurements and of temperature fields on the cylindrical surface recording. Under surface discharge action on cylindrical surface in the quiescent air, the flow accompanied by the formation of a near-wall vortex structure and a set of the radially-oriented jets is visualized. The observed jets leave the thermal boundary layer and are able to influence to the gas areas located far away. The presented results indicate the effectiveness of the surface discharges use to control gas-dynamic, thermo-physical and mass transfer processes in the vicinity of streamlined bodies such as cylinders.

1. Introduction
In the present, surface discharges are used in various fields of science and technology [1–3]. These discharges excite laser active mediums [4], process materials and synthesize substances [5, 6], generate UV radiation and heat [7, 8]. However, the efficiency of the developed gas-discharge devices based on surface discharge depends on heat and mass transfer processes in interface of plasma layer and neutral gas as well as in the interface between plasma layer and solid dielectric [9, 10]. Thus, the study of phenomena in vicinity of the plasma sheet is an important problem for the physics and chemistry of gas-discharge processes.

One of the surface discharge applications is associated with the generation of plasma-induced gas streams for the near-wall flow transformation [11, 12]. According to [13–15], the surface discharges are able to generate spatially-oriented jets in boundary layer. In case of the asymmetric type electrode system [11, 13], the surface discharges form the tangentially-directed jets propagated along dielectric surface, by accelerating gas in the near-wall area. While the colliding surface discharge electrode system [16] forms jets oriented along normal to dielectric surface [14, 15]. Such jets are capable to leave boundary layer by influencing to the flow core. Thus, gas-discharge devices based on surface discharges may move gas masses to the distances significantly exceeding the thickness of the boundary layer, by influencing to the heat and mass transfer processes at the wall. This phenomenon leads to the necessity of study of electro-physical and gas-dynamic processes in surface discharge by various methods in order to improve properties and operational modes of gas-discharge systems [15, 16].

For planar electrode systems, these results were obtained and discussed in [11–14]. In contrast to the mentioned papers, our article analyzes the electro-physical and gas-dynamic processes around cylinder under the colliding surface discharge action [16] because of reduction possibility for bluff
bodies drag in the subsonic flow. According to [17], the circular cylinder in subsonic cross-flow is typical bluff body which has significant aerodynamic drag coefficient \( C_D \approx 1 \) at \( Re = 1 \text{--} 200 \text{ k} \). Due to the active influence on the boundary layer around the circular cylinder, it is possible to change and control its aerodynamic characteristics by means surface discharges action. It is confirmed by papers [18--21]. However, in order to understand the possibilities of surface discharges in a flow, also it is necessary to study the gas-discharge process in a still atmosphere [15, 19]. It allows us to reveal the peculiarities of plasma-gas interaction providing conversion of surface discharge power to the flow energy.

2. Experimental setup

It is well known that the qualitative information about flow formation may be obtained by means of optical visualization [22]. Visualization is able to provide the spatial and temporal registration of the flow parameters [23]. Nevertheless, in order to visualize the several physical fields in flow simultaneously, it is necessary to use the set of different instruments and apparatus. Therefore, it is necessary to solve the unitization problem of instrumentation used in the experiment.

For complex study of the colliding surface discharges excitation in cylindrical geometry of electrodes and visualization of its interaction with surrounding air, the universal gas-discharge system was proposed. The gas-discharge system consisted of cylindrical, aerodynamic model, high-voltage power supply, equipment for discharge registration mode as well as systems for qualitative and quantitative optical visualization of flows.

Aerodynamic model (see figure 1, figure 2(a) and figure 3) was a cylindrical body with diameter \( D = 32 \text{ mm} \) and length \( L = 170 \text{ mm} \) formed by kit of parts (1)--(11) in figure 1. According to [17], the selected ratio \( L/D > 5 \) guaranteed a two-dimensional flow formation around cylinder when a surface discharge electrode system with cylindrical symmetry was used. The electrode system for the surface discharge excitation [16] was placed on the cylindrical surface of the aerodynamic model. The electrode system included discharge electrode (1) consisting of ten linear segments, kapton dielectric barrier (2) with thickness of 320 \( \mu \text{ m} \), and the grounded screen (3). Ten segments of discharge electrode (1) were deposited along the generatrix lines on cylindrical surface of aerodynamic model and had angular step around \( \Delta \alpha = 36^\circ \). These segments (1) were connected to the high-voltage power supply (12) via high-voltage bus (9) while the grounded screen was connected with the earth via conductive stud pin (6) and sleeve (7).

The colliding surface discharge (see figure 2(b)) was excited under alternating voltage action \((|U| < 3.5 \text{ kV} \) and \( f \approx 8 \text{ kHz} \)). If it is necessary, the discharge generation modes were varied by means of the dielectric barrier capacitance change and the power supply control.

![Figure 1. Aerodynamic model scheme: 1 – discharge electrode, 2 – dielectric barrier, 3 – grounded electrode (screen), 4 – nose cone, 5,11 – screw nuts, 6 – stud pin, 7 – conductive sleeve, 8 – isolator, 9 – high-voltage bus, 10 – light-absorbing screen, 12 – high-voltage power supply.](image)
3. Results and discussion

According to [22, 27], the averaged and instant flow patterns are the valuable data source, that may be used in the analysis of the gas-dynamic processes in boundary layer. The averaged flow patterns are useful for studying the flow structure in a steady-state mode of surface discharge generation. While the
Figure 6. The averaged flow velocity near cylindrical body under surface discharge action with power consumption $W = 8.2$ Watt (a) and $W = 39$ Watt (b): 1 – cylinder, 2 – radially-oriented jets, 3 – vortex structure.

Instant flow patterns may be used to describe the evolution of transient processes. In the present paper, the steady-state discharge generation modes were studied by the PIV method, and the shadow method was applied to visualize the flow modification after the surface discharge initiation.

In both cases, the gas-dynamic processes visualization was carried out at the atmospheric pressure ($P = 10^5$ Pa), temperature of 15–20°C and humidity of 20–25%. In these conditions, the surface discharge voltage-current characteristic presented in figure 5 was obtained. At voltage $|U_a| \approx 2$ kV, discharge appeared in the inter-electrode gaps on cylinder and had a maximum intensity of its radiation at $|U_a| \approx 3.4$ kV (see figure 2(b)). According to figure 5, the presented voltage-current characteristic was typical for dielectric barrier discharge [24]. Before the discharge ignition, average current $I_m$ had been changing practically linearly and was dependent on the capacity of the dielectric barrier. At the moment of discharge initiation, filling the discharge electrode's perimeter with plasma structures led to a significant increase in $I_m$. Another consequence of discharge excitation was the increase in the consumed active power from 8 to 40 Watt [29].

The PIV-registration of flows generated by the colliding surface discharge was realized at the minimum ($W = 8.2$ Watt) and maximum ($W = 39$ Watt) levels of discharge power consumption. These recordings were obtained in atmosphere seeded by oil particles and illuminated by laser sheet with the laser pulse energy of 30 mJ and a repetition rate of 8 Hz. The recorded images (25 frames in series) were processed using a cross-correlative algorithm with sampling window size of $32 \times 32$ pixels and window overlap of 50%. Further, the obtained vector maps of velocities were averaged.

In experiments, aerodynamic model was illuminated by laser sheet in the central part of cylinder at the distance around 85–90 mm from the light-absorbing screen (see figure 2). The laser sheet thickness (8–10 mm) was much more than displacement of the oil particles ($\approx 0.5$ mm) between the laser pulses in PIV-registration process. The wide laser sheet eliminated information loss about medium movement due to the change in the brightness of the oil particles images when they crossed the laser sheet moving along the axis of the cylinder [28]. Also, it allowed us to avoid the information loss due to the redistribution of the radiation intensity in the laser sheet under refraction action near the surface of the heated bodies. The absence of invalid velocity vectors near the cylinder surface (see figure 6) indicates the effectiveness of the used method.

The results of PIV-registration are presented in figure 6. For discharge power consumption of 8.2 Watt, the regular vortex structure formed near the cylinder surface. In accordance with vortex conservation theorem [30], the number of observed vortices was even and depended on the number of inter-electrode gaps. The flow velocity in the vortices was low and didn’t exceed 0.3 mps (figure 6(a)). In the vicinity of the cylinder, the air was uniformly illuminated by the primary radiation from PIV-
laser (Solo-150TX) and the secondary radiation reflected from the mirror. The flow velocity maximum was observed near the cylinder surface while at a distance of 15–20 mm there were zones with flow velocities of about 0.03–0.05 m/s (see dark areas in figure 6). There was also some nonuniformity in the flow generation along the cylindrical surface of aerodynamic model (see figure 6(a)). On the one hand, this is due to the different action of the Archimedes force to the flow in the upper and lower air areas near the aerodynamic model. On the other hand, it was associated with the quality of the aerodynamic model production, which changed from time to time at the manufacturing process.

At the same time, the surface discharge with power consumption of 39 Watt produced around aerodynamic model cylindrical surface both regular vortex structure and radially-directed jets leaving area in vicinity of cylinder (figure 6(b)). The jets propagated to the distance more than 60 mm and had velocity value in the exit region jet around 0.4–0.5 m/s. Also, the surface discharge heating due to thermal convection influenced the jets produced by the discharge on aerodynamic model. As a result, the radially-oriented jets strongly fluctuated as in direction as in intensity. In this way, the operation of the electrode system on the cylindrical surface was different from the flat electrode system action in [15]. Due to this effect, the flow acceleration downstream of the jet is observed in figure 6(b). Therefore, the flow pattern presented in figure 6(b) may only be used to demonstrate the qualitative structure of the generated flow.

The flow evolution after surface discharge start was investigated by the shadow method with continuous illumination of the gas in the vicinity of the cylinder. In order to effectively identify processes in the vicinity of the cylinder by using the shadow method, it is necessary to use heated air volumes providing the gradient of the air refractive index in registration. These conditions could be obtained in the heated boundary layer formed on the cooling, cylindrical surface after the surface discharge generation. Obviously, the gradient of the air refractive index in the boundary layer will depend on the processes of molecular diffusion and the surface temperature of the dielectric barrier. According to figure 7, the dielectric barrier surface during discharge generation was heating up to temperature of 40–75 °C. In these conditions, it was sufficient for formation of a heated gas layer with a thickness of 5–8 mm (see figure 8(a)).

The flow evolution near cylinder after the colliding surface discharge start is presented in figure 8. Here, the recorded process consists of several stages. At the first stage (figure 8(b) and figure 8(c)), in the heated boundary layer the vortex structures are formed. During 10 ms (figure 8(d) and figure 8(e)), the vortex structures increase in size and destroy the outer shell of the thermal boundary layer visualizing the position of the radial jets on the cylinder body (figure 8(f)). According figure 8, the whole process of gas flow modification takes around 25–35 ms.

Characteristically, the observed process in the cylindrical geometry of electrode system for the colliding surface discharge excitation is similar to the initial stage of flow formation in single DBD plasma actuator [31]. Initially, the starting vortices are formed in the inter-electrode gap and then are

![Figure 7](image-url)  
**Figure 7.** Infrared imagers of aerodynamic model cylindrical surface at different levels of the surface discharge power consumption: a – $W = 8.4$ Watt; b – $W = 39.2$ Watt. 1 – Side view of aerodynamic model; 2 – reflection of lateral model surface; 3 – auxiliary mirror; 4 – shadow from the model support. $T_b$ – brightness temperature.
Figure 8. Flow evolution around cylinder visualized by shadow method after the colliding surface discharge start: \( a - \tau = 0 \); \( b - \tau = 5 \) ms; \( c - \tau = 15 \) ms; \( d - \tau = 25 \) ms; \( e - \tau = 35 \) ms; \( f - \tau = 75 \) ms. 1 – aerodynamic model, 2 – heated boundary layer, 3 – vortex structure, 4 – jets. Frame rate during video-registration is 200 fps.

replaced by a spatially-oriented jet flow. However, the initial stage of the flow formation phase (during several discharge cycle) wasn’t disclosed in this study. In our case, initial phase of flow formation under the colliding surface discharges action is complicated by the electro-physical processes of interaction of single-charged plasma structures as well as their interaction with charges deposited on the dielectric surface. For such process investigation, the improvement of methods for near-wall streams recording is necessary. In particular, it is necessary to synchronize the high-speed camera with the discharge excitation system. It may be the subject of future research.

4. Conclusions
For a comprehensive study of the interaction between the colliding surface discharge and still air in the electrode system with cylindrical symmetry, the universal gas-discharge system has been developed. The system includes an aerodynamic model of cylinder body with a surface discharge electrode system on the side surface, the high-voltage power supply, and the means for surface discharge registration mode. The developed gas-discharge system may be useful in research of the heat and mass transfer in non-equilibrium media by various optical methods, including PIV, LDA, ESPI and shadow techniques.

For stationary regimes of surface discharge generation, flow registration in vicinity of the cylinder was carried out by the PIV method. It is experimentally shown that the low energy discharge consumption \( W = 8.2 \) Watt is leading to formation of a regular vortex structure around the lateral surface of the aerodynamic model. At the same time, an increase in the discharge power consumption
(up to 39 Watt) is providing the generation of radial jets leaving the near-wall zone near cylinder while maintaining the regular vortex structure at the cylindrical surface of the model. In practice, the observed flow structure may be used for intensification heat and mass transfer due to air mixing by the near-wall vortex structure. It may be useful in the development of plasma-chemical generators and heat-exchange devices.

By shadow visualisation method, it is shown that gas motion formed around cylinder after surface discharge activation leads to flow evolution from a regular vortex near-wall structure to radially-oriented jet flows. In this case, flow modification process is finishing during several tens of milliseconds after surface discharge start. The high-speed, flow modification in vicinity of bluff body (cylinder) permits us to design the long-lived, gas-discharge devices based on low-current, surface discharge for real-time drag reduction control or instant heat-mass transfer intensification.

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