Journal of Engineering Physics and Thermophysics, Vol. 82, No. 4, 2009

HYDROGASDYNAMICS IN TECHNOLOGICAL PROCESSES

AERODYNAMIC DRAG OF A PLATE IN AN IONIZED GAS FLOW INDUCED BY A NEAR-SURFACE HIGH-FREQUENCY BARRIER DISCHARGE

P. P. Khramtsov, O. G. Penyazkov, M. Yu. Chernik, V. M. Gritsenko, I. N. Shatan, and I. A. Shikh

UDC 533.9.082.5; 537.523.2

We have made an experimental study of the dependence of the total drag of a flat plate on the incident flow velocity and electrical parameters of discharge in the presence of a high-frequency barrier discharge on the surface. It has been shown that the use of a near-surface barrier discharge permits decreasing the profile drag coefficient by 3–7%.

Keywords: *aerodynamic drag, barrier discharge, plasma.*

Introduction. The application of gas discharge plasma for decreasing the aerodynamic drag of flying vehicles is a vast and actively developing field of research conducted all over the world [1–6].

Among the numerous methods of near-surface plasma formation noteworthy is the method of high-frequency barrier atmospheric-pressure discharge, which is used successfully not only to decrease the drag but also to sterilize surfaces infected with microorganisms and viruses in the food industry and public health services, as well as to improve the properties of various materials [1].

A barrier discharge permits creating nonequilibrium conditions in a plasma at atmospheric pressure. Depending on the properties of the gas, the control parameters, and the boundary conditions, the discharge can have a filamentary, regular, or diffusion form [2].

One of the main problems of the physics of gas discharge is initiating stable large-volume nonequilibrium plasma sources at a high pressure. The creation of a spatially homogeneous discharge is a topical problem, since unlike a filamentary discharge, it is much easier to control the plasma parameters in it, which simplifies its application in the industrial production and engineering design of flying vehicles. The problem is that with increasing pressure or volume a glow discharge can progress, with a high probability, to a contracted state in which the current propagates only in narrow glowing filaments, or even to an arc discharge [6].

In most cases, the barrier discharge is filamentary. For the discharge (not necessarily barrier) to be homogeneous, the presence of a fairly large number of electrons in the region before the breakdown is required. These electrons appear as a consequence of different processes: they may remain from a previous discharge, be formed in the process of collisions, or arise as a result of the emission from a dielectric discharge.

Atmospheric-pressure discharge diagnostics is a complicated problem. A homogeneous barrier discharge (atmospheric-pressure glow discharge) can be modeled with the use of hydrodynamic equations. The barrier discharge model makes it possible to gain a better understanding of both the dynamics of the discharge characteristics and the plasma-chemical processes proceeding in it.

We should note two types of homogeneous barrier discharge, which can tentatively be called Townsend and glow discharges. In the first case, the current is much lower (of the order of a few millimeters) than in the second case. Nevertheless, this value considerably exceeds the analogous characteristic in the ordinary Townsend low-pressure discharge and that of the direct current. The chief property of this discharge is that the electric field in it is not distorted by the space charge.

A. V. Luikov Heat and Mass Transfer Institute, National Academy of Sciences of Belarus, 15 P. Brovka Str., Minsk, 220072, Belarus. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 82, No. 4, pp. 726–731, July–August, 2009. Original article submitted September 5, 2008.

1062-0125/09/8204-0722©2009 Springer Science+Business Media, Inc.

At present of principal interest for investigations are plasma-chemical processes proceeding in the barrier discharge in various gaseous mixtures, since an understanding of these processes is necessary for creating industrial reactors for different purposes [7].

The problem of flame control with discharges, including nonequilibrium ones, arouses great interest among scientists all over the world. The main directions of investigations are widening of the explosive range and combustion of poor fuels at low temperatures [7]. In the literature, two main mechanisms of influence of the discharge on the flame are proposed: heating by discharge and synthesis of "active particles." More effective in terms of energy is the action on the flame of "active particles" and radicals formed on characteristic times of about 100 nsec and leading to an increase in the rate of reactions. Therefore, in [7] a barrier discharge in the presence of strongly nonequilibrium excitation of the gas components practically without heating was investigated.

Among the inhomogeneous discharges, of dominant interest is the microwave discharge which, depending on the gas pressure, can be glow or filamentary. The most effective discharge is the filamentary upstream discharge in the center of the model.

For a small decrease in the drag (by about 5%) in the turbulent boundary layer at longitudinal Reynolds numbers of $\sim 10^6$, ionic wind on a flat plane was used. At lower Reynolds numbers ($\sim 10^5$) by means of a corona discharge between spatially separated wires on a flat surface both in the case of direct current and for low-frequency (60 Hz) alternating current a decrease in the viscous drag of the flow up to 50% turned out to be possible [8]. The application of each of these methods is limited by the low Reynolds numbers because of the difficulty of estimating the influence of the corona discharge on high flow velocities.

Plasma actuators are created on the basis of corona, dielectric barrier, and homogeneous glow atmospheric-pressure discharges. Various configurations of these discharges were used for reducing the drag [9–13], for back pressing of the flow in turbines, on helicopter wings and blades, as well as for modifying the shock wave front in passing through the sound barrier.

The application of plasma actuators makes it possible to provide electrodynamic coupling between the electric field in the plasma and the neutral gas in the boundary layer [14–16]. This interaction is strong enough to cause effects important from the point of view of aerodynamics, including an increase or a decrease in the aerodynamics drag on a flat plate [17], regrouping of the flow near the wing at high angles of attack, and peristaltic induction of the neutral gas flow by a moving electrostatic wave on a streamline surface.

The aim of the present work was to investigate experimentally the dependence of the total aerodynamic drag of a flat plate in the presence on the surface of a high-frequency barrier discharge on the incident flow velocity and electrical parameters of the discharge.

Experimental Equipment and Measuring Methods. For the object of investigation, we used a smooth Caprolon plate of thickness 10 mm and dimensions 180 × 120 mm. On the sharpened front edge a system of needle electrodes spaced at 3 mm was mounted parallel to the surface at a height of 3 mm on either side of the plate. The second electrode represented a portion of copper wire covered with a fluoroplastic insulator built into the plate parallel to the front edge at a distance of 40 mm from the ends of the needle electrodes.

A high-frequency barrier discharge on the plate was formed as a result of applying to the electrodes periodic high-voltage pulses of duration 200 μsec, amplitude voltage 70 kV, and repetition frequency 1 kHz. As a result of the interaction between the charged particles and the field of electrodynamic mass forces, a direct gas flow (whose velocity was 5–10 m/sec) appeared in the discharge, with the formation of a turbulent boundary layer on the surface [18]. The plate was blown over by a two-dimensional air jet flowing out of a nozzle with an outlet cross-section of 15 × 200 mm. The experimental facility for measuring the aerodynamic drag is chemically represented in Fig. 1. Compressed air from a high-pressure line was fed through a system of cleaning filters 1, 2 into a receiver 3 of volume 0.2 m^3. The working pressure in the receiver was set depending on the required blow velocity. In the course of the experiment, the receiver discharged into the nozzle-feeding line 4 through a controllable quick-acting high-pressure valve 5. The plate was installed along the jet axis at a distance of 120 mm from the nozzle exit section and fixed on a hinge mechanically connected to a strain gauge 6. The velocity of the blowing stream was controlled by a Pitot–Prandtl tube. The electric gauge signal proportional to the value of the total aerodynamic drag of the plate was recorded by a digital oscilloscope 7. Calibration of the gauge was carried out with the aid of an analytical balance. Figure 2 shows a shadow pattern of the blow-over of a flat plate by a two-dimensional air jet in the presence of a barrier discharge. The

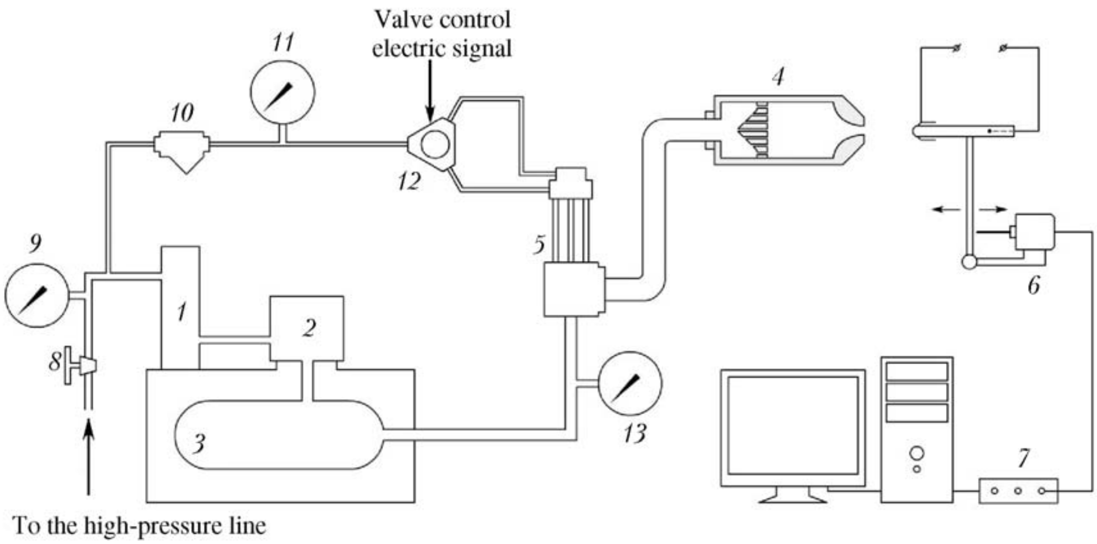


Fig. 1. Experimental facility for measuring the aerodynamic drag: 1) cleaning filter; 2) drying filter; 3) receiver; 4) nozzle; 5) quick-acting high-pressure valve; 6) strain gauge; 7) digital oscilloscope; 8) cock; 9) high-pressure manometer; 10) reducer; 11) control pressure manometer; 12) control valve; 13) manometer of receiver pressure.

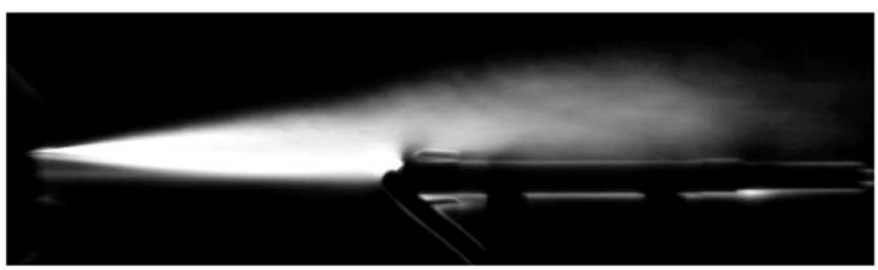


Fig. 2. Shadow pattern of the process of blow-over of a flat plate by a two-dimensional air jet.

jet velocity in the vicinity of the front edge was u = 60 m/sec. As follows from visual observations on a shadow device, the presence of a barrier discharge causes pressing of the boundary layer to the surface.

Measurement Data and Discussion. To estimate the influence of the incident flow on the structure of the barrier discharge, we took photographs of its proper glow in both the presence and absence of the air flow. Figure 3 presents photographs of the barrier discharge in the absence of the incident flow and at an air flow velocity u = 60 m/sec. As may be seen from the photographs, the presence of the air flow leads to an extension of the region of discharge glow by about 15% in the direction of the incident flow. The total aerodynamic drag of the plate was measured by an electromechanical strain gauge whose output signal was recorded by the digital oscilloscope. The plate was alternately blown over in the presence and absence of a discharge. The incident flow velocity gradually decreased as the receiver was discharged.

Figure 4 shows the characteristic time dependences of the total aerodynamic drag of the plate for both the above-mentioned cases. The profile drag coefficient of the plate was calculated by the formula [19, 20]

$$c_W = \frac{W}{\rho u^2 bh}\,.$$

Figure 5 gives the dependence of the profile drag coefficient of the plate on the Reynolds number in the presence (1) and in the absence (2) of a barrier discharge. The electric power input into the discharge was 100 W. As is

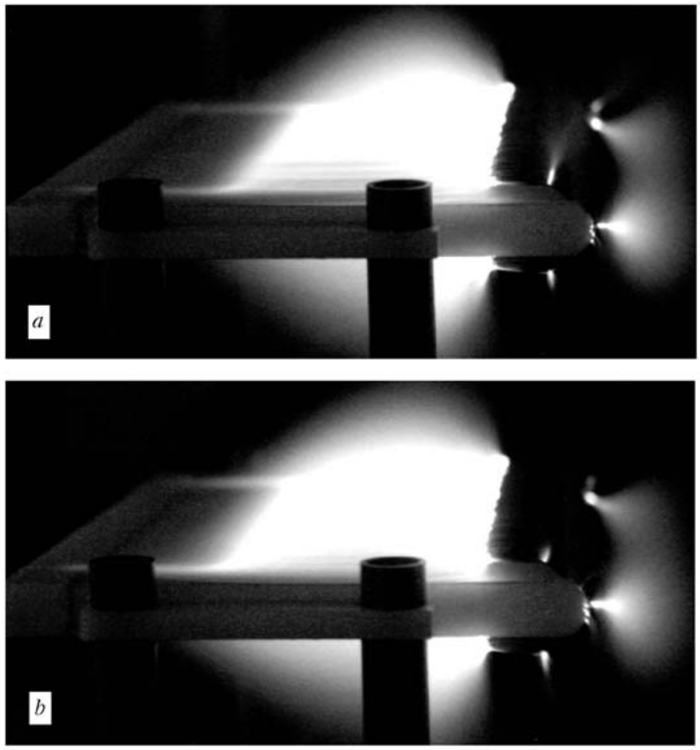
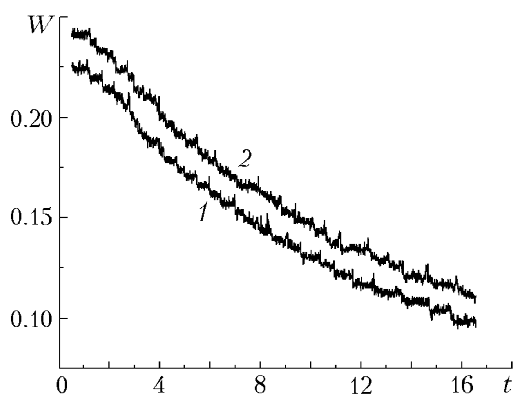


Fig. 3. Photographs of the proper glow of the barrier discharge: 1) in the absence of the incident flow; 2) at a blow velocity u = 60 m/sec.



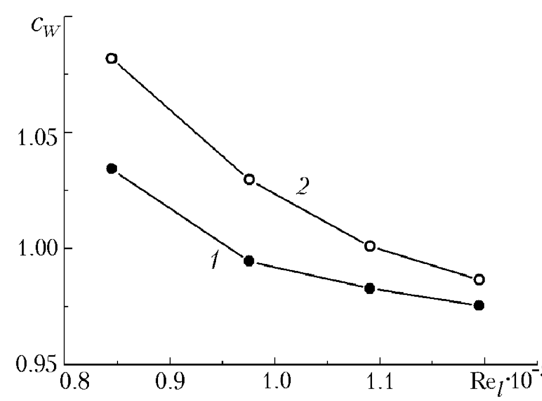


Fig. 4. Time dependences of the total aerodynamic drag of the plate in the presence (1) and in the absence (2) of a discharge. W, N; t, sec.

Fig. 5. Dependence of the profile drag coefficient of the plate on the Reynolds number in the presence (1) and in the absence (2) of a barrier discharge.

seen from Fig. 5, the presence of a high-frequency barrier discharge on the plate surface leads to a decrease in the profile drag coefficient by about 3–7%. It should be noted that in the investigated range of Reynolds numbers the profile drag is the sum of two components comparable in value: friction drag and pressure drag.

Since the surface layer of the plasma formed by the investigated configuration of discharge electrodes does not influence the value of the pressure drag, the data obtained point to the high efficiency of using a barrier discharge for decreasing the aerodynamic friction drag on the surface of the aerodynamic model.

To elucidate the most optimal glow conditions for the discharge from the point of view of its influence on the aerodynamic drag value, we investigated the dependence of the profile drag coefficient of the plate on the electric

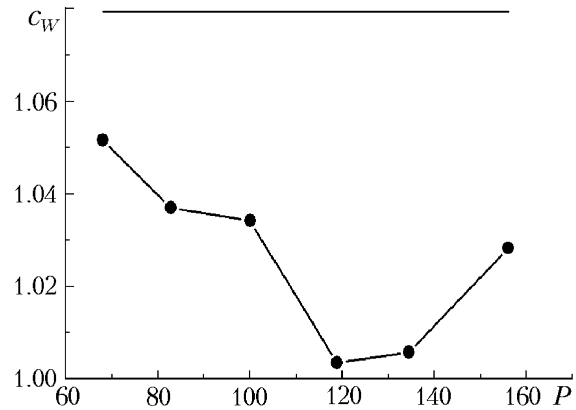


Fig. 6. Dependence of the profile drag coefficient of the plate on the electric power input into the discharge at u = 10 m/sec. P, W.

power input into the discharge. The results obtained are presented in Fig. 6, where the horizontal line corresponds to the value of the aerodynamic drag in the absence of discharge. With increasing electric power the efficiency of the influence of the barrier discharge on the aerodynamic drag of the plate increases up to a certain critical value of the specific surface input energy density p_c = 9.5 kW/m^2. A further increase in the electric power leads to an increase in the total aerodynamic drag of the plate, which is due to the processes of gas discharge plasma contraction in the self-magnetic field and the formation of filamentary structures in the discharge. The latter shunt the discharge gap because of their high electrical conduction, which leads to a decrease in the discharge glow voltage. Under these conditions the electric power input into the discharge gap is largely expended in heating the plasma, and the portion of the energy expended in forming the ionic wind decreases.

Conclusions. As a result of the experiments performed, it has been established that the use of a high-frequency near-surface barrier discharge permits decreasing the profile drag coefficient of the plate by 3–7%. The discharge is locked to the electrodes and practically is not blown off by the incident flow. The fairly high value of the critical specific surface input energy density p_c, upon reaching which the efficiency of the influence of the barrier discharge on the aerodynamic drag begins to decrease, makes it possible to use it in the engineering designing of flying vehicles in a wide range of electrical parameters.

This work was supported by the Foundation for Basic Research of the Republic of Belarus and by the Russian Foundation for Basic Research, project No. T083-222.

NOTATION

b, width of the plate, m; c_W, aerodynamic drag coefficient of the plate; h, thickness of the plate, m; P, electric power, W; p, surface input energy density, W/m^2; Re_l, Reynolds number calculated along the length of the plate; t, time, sec; u, incident flow velocity, m/sec; W, profile aerodynamic drag, N; ρ, air density, kg/m^3. Subscripts: c, critical.

REFERENCES

1. J. R. Roth, Plasma processing applications of a one atmosphere uniform glow discharge plasma, *Int. Symp. Plasma*, 19–21 September, 2001, Warsaw, Poland (2001), pp. 244–259.
2. V. M. Fadeev, U. Yusupaliev, and S. A. Shuteev, *Barrier Discharge in Modern Technology* [Electronic Resource] (http://www.optics.phis.spbu.ru/).
3. E. Bubnov, D. Udovenko, K. Sharshembiev, and M. K. Borombaev, The volt-Coulomb characteristic of a barrier discharge in a twin cable, in: *Proc. 1st Republican Sci. Conf. of Students Physics and Young Scientists*, Supplement to the Journal "Vestnik IGU," Karakol (2001), pp. 92–101.

4. V. T. Samoilovich, V. I. Gibalov, and K. V. Kozlov, *Physical Chemistry of Barrier Discharge* [in Russian], Izd. MGU, Moscow (1989).
5. Yu. V. Filippov and Yu. M. Emel'yanov, On the active power of ozonizers, *Zh. Fiz. Khim.*, **33**, No. 5, 1042–1046 (1959).
6. *Homogeneous Barrier Discharge* [Electronic Resource] (http://www.optics.phis.spbu.ru/).
7. E. I. Mintusov, A. A. Nikipelov, and S. E. Yankina, Influence of a nanosecond barrier discharge on the kinetics of reacting flows, *Collected papers of scientific sessions of Moscow Engineering Physics Institute–2007*, Moskovsk. Inzh.-Fiz. Inst., Moscow (2007), pp. 30–32.
8. S. El-Khabiry and G. M. Colver, Drag reduction by dc corona discharge along an electrically conductive flat plate for small Reynolds number flow, *Phys. Fluids*, **9**, No. 3, 587–599 (1997).
9. M. R. Dhanak and C. Si, On reduction of turbulent wall friction through spanwise wall oscillations, *J. Fluid Mech.*, **383**, 175–195 (1999).
10. J. R. Roth, *Industrial Plasma Engineering*, Vol. 1. *Principles*, Institute of Physics Publishing, Bristol, Philadelphia (1995), pp. 453–461.
11. Y. Du and G. E. Karniadakis, Drag reduction in wall-bounded turbulence via a transverse travelling wave, *J. Fluid Mech.*, **457**, 1–34 (2002).
12. A. Soldati and S. Banerjee, Turbulence modification by large-scale organized electrohydrodynamic flows, *Phys. Fluids*, **10**, No. 7, 1742–1756 (1998).
13. M. Fulgosi, A. Soldati, and S. Banerjee, Turbulence modulation by an array of large-scale streamwise structures of EHD origin, *Proc. FEDSM 99 3rd ASME/JSME Joint Fluids Engineering Conf.*, 18–23 July, 1999, San Francisco, CA (1999), pp. 1–8.
14. J. R. Roth, *Method and Apparatus for Covering Bodies with a Uniform Glow Discharge Plasma and Applications Thereof*, US Patent 5,669,583, Sept. 23, 1997.
15. D. M. Sherman, S. P. Wilkinson, and J. R. Roth, *Paraelectric Gas Flow Accelerator*, US Patent 6,200,539 B1, March 13, 2001.
16. C. Liu and J. R. Roth, Atmospheric glow discharge plasma for aerodynamic boundary layer control, *Proc. 21st IEEE Int. Conf. on Plasma Science*, 6–8 June, 1994, Santa Fe, NM, Paper 1P-26, ISBN 7803-2006-9. Pp. 97–98.
17. J. R. Roth, D. M. Sherman, and S. P. Wilkinson, Electrohydrodynamic flow control with a glow-discharge surface plasma, *AIAA J.*, **38**, No. 7, 1166–1172 (2000).
18. P. P. Khramtsov, O. G. Penyazkov, M. V. Doroshko, M. Yu. Chernik, and I. A. Shikh, Shadow method for measuring the averaged concentration of electrons in an ionized gas flow induced by a high-frequency barrier discharge, *Inzh.-Fiz. Zh.*, **82**, No. 2, 364–370 (2009).
19. H. Huntley, *Dimensional Analysis* [Russian translation], Mir, Moscow (1970).
20. H. Schlichting, *Boundary Layer Theory* [Russian translation], Nauka, Moscow (1969).