The influence of plasma actuators material and geometry on the electromagnetic characteristics of the discharge and the specific thrust of synthetic jets

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Abstract. It was examined the effect of electrode material on the value of specific thrust of the synthetic jets produced by symmetric actuator. The dependences of specific thrust on the distance between external electrodes for copper, aluminium, nickel and titanium was made. A considerable effect of the shape of the external electrodes on the electric field and current density in the tape drive and the specific thrust of the synthetic jet were investigated. The role of autoelectronic emission on the current in streamers and the value of volume force acting on the stream were also evaluated.

1. Introduction
The characteristics of synthetic jets generated by plasma actuators have been studied in a number of works, in which the variable factors included electrodynamic parameters (voltage applied to exposed electrodes, frequency) [1] and actuator configuration (spacing between exposed electrodes, dielectric layer thickness, gap width between the exposed and encapsulated electrodes) [2, 3], while much less attention has been given to the material of electrodes. The formation of a synthetic jet begins primarily with the release of electrons from the electrode surface [1], which implies that the ionization energy of atoms of the electrode material significantly influences the power of a jet emitted by the actuator. A significant role can also be played by the resistivity of electrode material [4], since it directly influences the efficiency of electric energy conversion into the kinetic energy of electrons and ions. In view of a low efficiency of the dielectric barrier discharge (∼ 0.1% [5]), even a small increase in this value can lead to a significant increase in the energy of a synthetic jet created in this discharge.

2. Experimental setup
Figure 1a shows the scheme of a symmetric actuator, which comprised of a 400 μm thick fluoroplastic plate 1 onto which 40 μm thick foil electrodes made of copper, aluminum, or nickel were glued. Upper (exposed) electrodes 2 had a width of 10 mm, while the width of the lower (encapsulated) electrode 3 was equal to gap width d between the upper electrodes. The exposed electrodes were connected by a high voltage cable via a 900 Ω ballast resistor to a controlled source of high AC voltage with a frequency of 50 kHz. The encapsulated electrode was grounded. The length of the discharge region along electrodes was within 12–14 cm.
Table 1. Electric and thrust parameters of different materials.

| Material | Resistivity, nΩ/m | Ionization energy, kJ/mol | Maximum value of the thrust of serpental configuration, mN/m | Maximum value of the thrust of linear configuration, mN/m |
|----------|-------------------|--------------------------|----------------------------------------------------------|--------------------------------------------------------|
| Copper   | 16.8              | 745.5                    | 8                                                        | 13.5                                                   |
| Aluminium| 28.2              | 577.5                    | 11.5                                                     | 16.9                                                   |
| Nickel   | 69.3              | 737.1                    | 13.5                                                     | 15.2                                                   |
| Titanium | 531.4             | 657.8                    | 14.2                                                     | 12.9                                                   |

Figure 1b presents a schematic diagram of the experimental setup used to measure the specific thrust of a synthetic jet created by the symmetric actuator. According to this, actuator 4 was mounted on electronic balance 5 and connected by high voltage wires 8 to high AC voltage source 6 via ballast resistor 7. When the applied voltage amplitude was increased to 6 kV, a dielectric barrier discharge appeared in the space between exposed electrodes and created a synthetic jet that was manifested by increasing weight of the actuator. The specific thrust \( f \) of the synthetic jet created by the actuator was defined as the ratio of an increase in the actuator weight to the length of the discharge region measured along the electrodes, where \( F \) is the actuator weight increment due to the thrust developed by the synthetic jet and \( L \) is the length of discharge along the electrodes.

3. Influence of exposed electrode material

The present work was aimed at studying the dependence of the specific thrust of a synthetic jet on the distance between external (exposed) electrodes of symmetric actuators with electrodes made of three materials possessing different resistivities and ionization energies. The values of these characteristics are presented in the table for copper, aluminium and nickel. Copper and nickel have close ionization energies, but significantly different resistivities. The ionization energy of aluminium is 20% lower than that of copper and nickel. All electrodes had the same thickness (40 μm) and width (10 mm).

Figure 2 shows plots of specific thrust \( f \) of a synthetic jet produced by symmetric actuators with copper, aluminium and nickel electrodes versus distance \( d \) between exposed electrodes for the applied AC voltage amplitude of 6 kV at a frequency of 50 kHz. The ionization energy for aluminium is significantly lower than that for copper, which results in the formation of a
greater number of free electrons (for the same applied voltage) in the actuator with aluminium electrodes. This leads to a higher degree of air ionization and a greater volume force acting upon the flow and creating the synthetic jet. As a result, the specific thrust of the synthetic jet is about 15% greater for aluminium electrodes at all values of the distance between exposed electrodes. The values of specific thrust in the region of the extremum for nickel are greater than those for copper.

Nickel possesses about a four times greater resistivity than copper at approximately the same ionization energy. Since the jets in our experiments were directed upward, convective flows introduced a positive contribution to the thrust developed by the synthetic jet and thus increased the efficiency of discharge—that is, the efficiency of conversion of the electric energy into kinetic energy of the synthetic jet. An increase in the distance between exposed electrodes leads to leveling of the specific thrust of actuators with copper and nickel electrodes. This is explained by the fact that an increase in the distance traveled by near-wall jets before collision leads to greater energy losses due to viscous forces and Joule heat fluxes from heated electrodes [6]. Thus, the positive effect observed under extremal conditions is counterbalanced by increased heat evolution from the surface of electrode. Based on the established dependences, it can be concluded that a decrease in the ionization energy of the electrode material and an increase in its resistivity favor an increase in the specific thrust of a synthetic jet produced by a symmetric plasma actuator. The maximum effect is achieved as an extremum with respect to the applied voltage, frequency, and distance between exposed electrodes.

4. On the geometry of the actuator
The electrodes in the previously reviewed actuators had linear form. In [7], the external electrode has a serpental shape, resulting in the increase of the wall jet maximum velocity. How the shape of electrodes affect on the value of the synthetic jets specific thrust of symmetrical actuators? Table 1 shows the maximum values for the specific thrust of the linear and serpental actuators for four different materials. Because of the uneven distribution of the field along the inner surface of the electrodes synthetic jet is divided into several jets directed perpendicular to the surface of the actuator, but localized in a circle with a diameter approximately equal to the distance between the exposed electrodes. In such scales imposition of the field leads to a decrease of the components of electric field directed along the surface of the dielectric. On the other hand there is a concentration of the electric field lines near the edges of the electrode, which leads to increasing autoemission current. Thus for electrodes made of materials with high resistivity thrust of the synthetic jet is significantly higher for serpentine configuration compared to linear.
5. Summary
It was found a significant influence of the material of exposed electrodes on the value of specific thrust of the synthetic jet. It was shown that the lesser the ionization energy of material of the exposed electrodes the greater the specific thrust. Specific thrust of synthetic jet has max relatively to the distance between the exposed electrodes for actuators with electrodes made of copper, aluminium and nickel, but for the titanium this max is not so noticeable. Specific thrust of synthetic jet produced by serpental actuators the higher then the larger resistivity of exposed electrodes up to 600 Ω mm²/m.

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