Journal of Electrostatics 95 (2018) 1–12

Contents lists available at ScienceDirect

Journal of Electrostatics

journal homepage: www.elsevier.com/locate/elstat

In-atmosphere electrohydrodynamic propulsion aircraft with wireless supply onboard

Vladislav Yu. Khomich, Igor E. Rebrov*

Federal State Budgetary Scientific Institution Institute for Electrophysics and Electric Power, Russian Academy of Sciences, St.-Petersburg, 191186, St.-Petersburg, Dvortsovaya naberezhnaya,18, Russia

ARTICLE INFO

Keywords:
Electrohydrodynamic thruster
Ionocraft
Asymmetric capacitor
Ionic air propulsion
Electrohydrodynamic flow
Wireless power

ABSTRACT

Electrohydrodynamic flow generation systems are widely investigated in aerodynamic application due their high reliability, simplicity and effectiveness. This paper describes a heavier-than-air non-aerodynamic aircraft on the basis of in-atmosphere electrohydrodynamic propulsion system with wireless power system onboard. Inspired by the fundamental knowledge of air propulsion principles, we numerically and then on a prototype demonstrated the possibility of creating such a device. It is achieved by a combination of the ionocraft airframe composed of symmetric drop-shaped collectors carrying a part of the mechanical load and the developed wireless power source with a high power density per unit mass.

1. Introduction

Recently there has been a growing interest in the development of electrohydrodynamic (EHD) control methods for gas flows [1–17]. Several areas of application are actively researched, namely the use of the ion wind for cooling of microelectronics [1,2], in laser technology [3,4], biomedical application [5,6], agriculture [7], scientific instrument making [8], chemical catalysis and in surface treatment technologies [9,10], in electrostatic precipitators and air ionizers [11], in solid-fluid boundary layer modification [12], ion drag pumping [13], in electro-acoustic speakers [14], water treatment system [15] and in many others [16]. In space technology, the electrokinetic flow is used in the development of electric propulsion systems [17].

Quite a few studies are dedicated to the development of atmospheric plasma technology on the basis of EHD-flows with great potential use in aeronautics [18]. This technology allows to control the air flow near the wing surface [19], reducing fuel consumption, increasing the speed of civil and military aircraft, its thrust and, as a result, the mass of payload and, finally, simplifying the airframe [20,21]. The possibilities for the use of the EHD-flow generating devices in propulsion applications are being explored as well with a view to the all-electric aircraft design [22].

Ionocraft is a typical representative of the aircraft operating on the basis of this principle [23]. Ionocraft or lifter is a heavier-than-air flying machine using an electrohydrodynamic flow to create downward thrust and to take off and land vertically. It combines the airframe with the propulsion system. The gas medium surrounding the device serves as the propellant for the lifter, and electricity is the only source of energy.

The wide popularity of the electrohydrodynamic devices research in the aerospace engineering is associated with their high reliability, simplicity of design and short response time due to a high speed of operation [24], fully electric action (there are no moving parts and wear-related failure of elements), absence of combustion processes for the thrust generation, and of course, sufficiently high efficiency of input energy conversion into kinetic energy of the flow [16,25]. Contemporary research suggests [26] that atmospheric pressure ion engines theoretically could achieve thrust-to-power ratio of 110 N/kW, whereas jet aircraft engines allow 2 N/kW ratio only. To date, the magnitude of the thrust produced by atmospheric EHD ion engines has reached 15 N per 1 kW of consumed power [27] and mechanical efficiency of more than 7.5% in the moving fluid [25]. Moreover, they are distinguished by stable operation in wide pressure range that is so important for aerodynamics [28]. All the above information allows us to make a conclusion about the relevance and prospects of studying the systems of electrohydrodynamic flows formation and aircraft based on them.

2. Formulation of the problem

Any system of EHD flows formation is composed of a plasma generator, an ion accelerator and a neutralizer cathode. These parts of the system can be made either of the separate independent units or as a single device. The most typical and popular ionocraft design is known

* Corresponding author.
E-mail address: rbrv.igor@gmail.com (I.E. Rebrov).

https://doi.org/10.1016/j.elstat.2018.07.005
Received 1 March 2018; Received in revised form 28 June 2018; Accepted 23 July 2018
0304-3886/

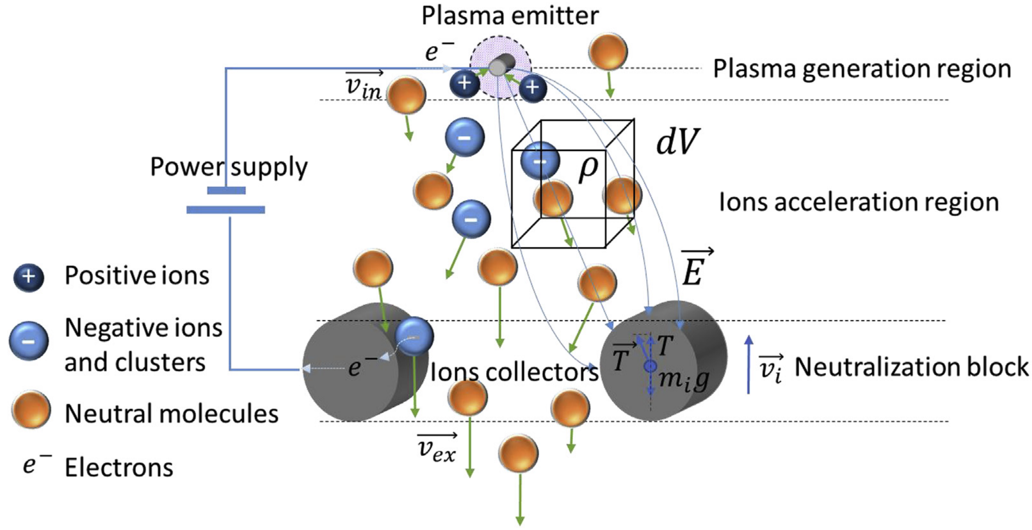

Fig. 1. EHD-cell in the form of an asymmetric capacitor with negative voltage polarity, system blocks and symbols for ions and neutral particles. Here dV is the small volume of the outer discharge region V of the cell, $\overrightarrow{E}$ is the vector of the electric field strength; ρ is the distribution function of the space charge density, $\overrightarrow{T}$ is the thrust vector and T is its vertical projection, g is the gravitational acceleration, m_i is lifter mass, v_{ex} is the exhaust speed of the EHD flow at the outlet of the ionocraft, v_{in} is the flow speed at the inlet of the device, v_i is the flight speed.

under the name of the "asymmetric capacitor" and includes two unequal-sized electrodes (an emitter and a collector of ions) spaced from each other by the interelectrode gap. This geometry combines all the blocks of the system into a single structure with a rigid mechanical connection and forms an EHD cell. The source of the plasma here is a corona discharge, ion acceleration and drift occurs in interelectrode gap, and neutralization - on a collector that can be cylindrical, planar, grid or possess some other shape with a large emitter facing radius.

A typical geometry of an asymmetric capacitor illustrated in Fig. 1. A constant voltage of tens of kilovolts is applied to the cell electrodes. When the intensity of a highly inhomogeneous electric field near an electrode with a large surface curvature (plasma emitter) crosses the threshold (about 30 kV/cm^2 for air), the gas is ionized in a small volume around it. The resulting positive and negative charges are in the electric field between the emitter and the collector, thus there begins a charged particles drift along force lines and collision momentum transfer to the neutral gas molecules. As a result, a low-temperature weakly ionized plasma region is formed in the interelectrode gap (in the outer region of corona discharge). The difference between the electric field work to transfer the differently charged ions from the plasma generation region to the collector on the one side and from that area to the emitter on the other side determines the dominant direction of the EHD flow. Reaching the collector electrode the charged particles drifting in the interelectrode gap become deionized, and continue their motion with gas beyond the cell in neutral form. The charges of the opposite sign, performing much less work, are neutralized on the emitter. The velocity of ion motion depends on the strength of the local electric field and their mobility. Because of their small mass, electrons are virtually not involved in the momentum transfer, but, along with photoionization, they make a decisive contribution to the ion formation process. The electric circuit of the device is made up of a constant voltage source, supply lines, electrodes and is closed via an equivalent non-linear load representing the plasma between the plasma emitter (PE) and the collector.

The device-thrown air creates a thrust sufficient to overcome gravity. The thrust T of the aircraft is equal and opposite to the change in its momentum in time, which is determined by the product of the EHD flow velocity increment relative to the ionocraft by the mass of the ejected gas $\dot{m}_g$ per unit second. Since the propellant flow-rate does not change the total mass of the thruster m_i, the balance of forces in static equilibrium can be written as follows:

$$m_i g = T = -\dot{m}_g (v_{ex} - v_{in} - v_i) \quad (1)$$

The thrust acting on the ionocraft can be calculated as the product volume density of charges ρ by the local electric field strength E and by integrating this expression over the entire volume of the discharge gap V [26].

$$T = \int^{V} E\rho \cdot dV = \int^{V} \frac{j}{\mu} \cdot dV \quad (2)$$

Where $j = E\rho\mu$ is the electric current density, μ is the air ion mobility.

The creation of autonomous self-lifting devices on EHD –thrust in atmospheric air with a high-voltage power supply onboard is currently hampered by a large mass of their structural elements and power storage units and a small power-to-weight ratio of the voltage converters. In this paper, we attempt to solve this problem by using a wireless energy transfer technology, a modern microelectronic component base capable of operating at high energy density, high voltages and frequencies, and also optimizing the weight and the geometry of the EHD cell.

3. Results

3.1. Analysis of the device performance factors

The design of the thruster's cell is critical for its functioning and is a compromise between its efficiency, weight and size. The main ionocraft parameters such as mass m_i, power consumption per unit length P/l_2, thrust T, effectiveness T/P are all related to the design of the EHD-cell and the voltage source, surrounding conditions (Fig. 2).

The main task is to select the optimal parameters of the system, resistant to environmental changes, and leading to simplicity of design, minimizing voltage and mass of the power source and airframe, maximizing the thrust.

The most important emitter parameters include its shape and size. Moreau [27] and colleagues found that a wire shape of the emitter has similar effectiveness with a periodic multi-point structure, but it is much simpler in manufacturing. The wire radius r_w determines the threshold of the corona inception voltage [27,29], which is satisfactorily described by the Peek's formula including changes in pressure and temperature [30,31]. The modern experimental study indicates [32] that the Peek's formula is applicable with small correction for