Thrust and thrust-to-power ratio in electrohydrodynamic propulsion electrode systems

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Abstract. The influence on thrust parameter and efficiency from geometric parameters and design features of the ionocraft electrode is considered, dependences were obtained. The most effective mode of work lifters of the considered structures is achieved at low current. The increase of distance between the corona electrode and the collector gives the growth of thrust and thrust-to-power ratio up to some distance. It is advisable to use emitters with smaller diameter to reduce losses to the formation of the corona.

1. Introduction
The ionocraft is a device that provides a lifting force due to the formation of the electrohydrodynamic (EHD) flow. EHD flow is a name for a physical phenomenon of collective motion of gas caused by a drift of charged particles in strong electric field and by transfer of their momentum to neutral environment. Generation of ions occurs in field of corona discharge, which is characterized by high heterogeneity of electric field in space. A typical scheme of this device consists of two conductive parts. The first one is represented by a thin wire or a tip, called a plasma emitter (PE) or corona electrode. The second one (the collector) is designed as a wire grid, a tube or a frame covered with foil. High voltage is applied to the corona electrode; which results ionization and subsequent transfer of electric field energy to ions occur that leads to the appearance of thrust. There are no moving parts in the ionocraft and surrounding atmosphere is working agent, thus only electric energy is converted. It would find application in flying micro-robots and autonomous aircrafts on solar batteries. Now there are not devices able to perform lifting of its own weight, including ionocraft power supply system. A design of the power supply implies low weight and high power-to-weight ratio for lifting of the device with the supply system and additional payload. Thus, optimization and simulation of each of such devices’ parts together is required for obtaining their high efficiency [1-3].

2. Numerical simulation
In this paper, we consider the influence on thrust parameter and efficiency from geometric parameters and design features of the ionocraft electrode systems (IES) in air at atmospheric pressure and natural humidity. Designs of IES models shown in Figure 1. They include the diameter of the corona electrode, the distance between it and the collector, the number of emitters in usage and the framework of the collector. Thrust parameter is represented by magnitude of a generated thrust \(F\) measured in grams, and the efficiency is evaluated by magnitude of thrust-to-power ratio, which is equal to ratio of thrust to power consumption \(F/P\) [g/W].
Dependences for the efficiency of the system and the magnitude of the thrust were obtained. During the research several systems have been examined, including one or two PE – nichrome wires with a diameter $d = 0.08$ mm and $d = 0.02$ mm and a series of collectors: one or two parallel aluminum tubes with a diameter $d_c = 10$ mm, a steel grid with a mesh size of $S = 2 \times 2$ mm$^2$ and a wire diameter $d_c = 0.42$ mm.

According to [4] formula for estimating thrust for ionocraft is as follows:

$$ F = \frac{I \cdot l}{\mu} $$  

(1)

where $I$ is intensity of current; $l$ is distance between PE and the collector; $\mu$ is ion mobility in air. Considering (1), it’s clear that thrust $F$ will increase in proportion to increasing distance $l$ if other parameters stay the same. In practice, this dependence cannot be fully performed (see Figure 2a, b).

Increasing of the zone of acceleration of charged particles leads to an increase of the thrust up to the distance of the collector-emitter 21 mm. As $l$ increases, the growth of thrust $F$ is slowing down.

Using (1) and expressions for power consumption and $I$–$V$ curve of corona discharge [5], thrust-to-power ratio for ionocraft is obtained:

$$ \frac{F}{P} = 2l(\mu V_k\left(1 + \sqrt{1 + \frac{4l}{CV_k^2}}\right))^{-1} $$  

(2)

where $V_k$ is the critical corona voltage and $C$ is a constant value defined for a particular geometry of the system. Hyperbolic dependence for thrust-to-power ratio from current shows necessity of work of ionocraft in modes small values of current $I$ as the most effective.
Dependences of the thrust and the efficiency of the system for different polarities of the corona and the distance between the collector and emitter is shown in Figure 3a, b.

![Figure 3. Thrust (a) and thrust-to-power ratio (b) depending on current for different distances between electrodes \( l \), mm for model 3: red – wire \( d = 0.08 \) mm, tube \( d_c = 10 \) mm, positive corona; blue – wire \( d = 0.08 \) mm, tube \( d_c = 10 \) mm, negative corona; yellow – wire \( d = 0.02 \) mm, tube \( d_c = 10 \) mm, negative corona](image)

At \( l = 9 \) mm, all types of devices showed approximately equal performance. With increasing \( l \), the system with a negative corona becomes more effective in comparison with the device with the positive corona with the similar configuration. This is due to the difference in composition of ions in the air for different polarities.

To assess power losses on the corona the ratio can be used [6]:

\[
P_{\text{losses}} = E_0 r_w l \delta \left( 1 + \frac{0.03}{\sqrt{\delta r_w}} \right) \ln \left( \frac{l}{r_w} \right)
\]

(3)

\[
\delta = \frac{0.392 p}{r}
\]

(4)

where \( P_{\text{losses}} \) is the power losses on the corona, W; \( E_0 \) is the intensity of the electric field at breakdown in the air, \( E_0 = 3 \times 10^6 \) V/m; \( r_w \) is the radius of emitter wire, m; \( I \) is the intensity of current, A; \( l \) is the distance between the corona electrode and the collector, m; \( p \) is the pressure, mm Hg and \( T \) is the temperature, K. So at \( l = 29 \) mm, \( I = 0.1 \) mA, the share of losses is: for emitter wire diameter \( d = 0.02 \) mm: \( \frac{P_{\text{losses}} \times 100}{p} \approx 12\% \); for emitter wire diameter \( d = 0.08 \) mm: \( \frac{P_{\text{losses}} \times 100}{p} \approx 21\% \).

Influence of configuration of IES on the efficiency of the system is shown on Figure 4a, b. Five models of IES have been compared. In all five models emitter wire with diameter \( d = 0.02 \) mm is under negative potential. The tube collector has diameter \( d_c = 10 \) mm. Results of the experiment show that thrust-to-power ratios of system with the grid collector and system with double tube collector are comparable, although for the last one a greater thrust value is observed at the same discharge current. Compared to the single tube collector such configurations give an increase of value of \( F/P \) to 1.5 – 2 times. Using of double PE leads to a drop of output parameters, and with decreasing distance between wires characteristics fall also. This is due to the mutual shielding of PE, when the ratio \( h/l \) is lower value of 1.15 [4].
Dependences of the thrust and the thrust-to-power ratio from power consumption is shown on Figure 5a, b. Note the ability to work in a wide range of currents and capacities in the system with a grid collector. The IES of this type has reached the maximum for this series of experiments of thrust to about 2.8 g.

3. Conclusion

The thrust and efficiency of ionocraft electrode systems is investigated for different working polarity of the corona electrode. The most effective mode of work lifters of the considered structures is achieved at low current. The thrust-to-power ratio reaches a value of 1.1 g/W. The increase of current, according to (2), leads to a decrease efficiency up to a value of 0.2 g/W. The increase of distance between the corona electrode and the collector gives the growth of thrust and thrust-to-power ratio up to 21 mm. In the subsequent distancing statistically significant increase of characteristics is not observed. It is advisable to use emitters with smaller diameter to reduce losses to the formation of the corona. The using of emitter with wire diameter $d = 0.02$ mm increase thrust-to-power ratio by 10% compared with wire diameter $d = 0.08$ mm. Collector in form of a grid or two parallel tubes gives a significant increase of thrust and thrust-to-power ratio of EHD propulsion system compared with the single tube collector.

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4. References

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