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COMMUNICATIONS

ON THE THRUST OF A SINGLE ELECTRODE ELECTROHYDRODYNAMIC THRUSTER

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Linear thrust generation by a single pin emitter electrode under AC excitation has been studied. Presented are thrust measurements of a single electrode thruster, in comparison with classical, two electrode electrohydrodynamic thruster. The experiments show comparable thrust for both configurations at low voltage levels, suggesting higher thrust-to-weight ratio of single electrode thrusters at low applied voltages. Further, a hypothesis of single electrode thrust creation is proposed.

Keywords: electrohydrodynamics, propulsion, corona discharge, asymmetric capacitor

1 INTRODUCTION

Ionic wind, which can be described as a movement of a gas or a liquid due to corona discharge, has been studied by Chattock as early as 1899 [1]. Nowadays termed Electrohydrodynamic (EHD) thrust, it is generated by direct coupling of electrical to mechanical energy. The utilization of EHD thrust for propulsion purposes was first proposed by T.T. Brown in the 1920s [2]. Recently, values of a thrust-to-power ratio higher than $100\,\mathrm{NkW}^{-1}$ have been measured [3], proving that thrusters with wire-cylinder geometry are able to outperform modern jet engines in terms of efficiency. However, the same cannot be said about parameters like thrust-to-weight ratio or thrust-per electrode area, which limit the potential use of this propulsion to specific applications.

Investigated thruster designs, have always implemented two or more electrodes and employed mostly DC voltage. More electrodes mean more weight, so it is worth asking, whether one electrode would not be enough. The idea of generating thrust by a single electrode is not new, since a corona pinwheel can be considered a single electrode thrust generating device. However it has not been considered as a candidate aerial propulsion system yet.

The purpose of this work is to investigate linear thrust generation by a single pin emitter electrode under AC excitation, with emphasis on propulsion applications.

2 THEORY

Every electrohydrodynamic device requires electrodes for electric field generation, ion source and a surrounding medium. Applying voltage across any two finite dimension electrodes leads to inhomogeneous electric field.

Higher field gradient in the vicinity of the electrode with smaller radius of curvature results in lower corona inception voltage compared to the other electrode [4]. When corona inception voltage is reached, corona discharge is ignited and the air around sharper electrode becomes ionized. Created ions are accelerated by electric field and give off gained momentum through collisions with neutral molecules. The surrounding liquid or gas starts to flow and by mechanism of action-reaction, thrust is created in opposite direction.

The mechanism of thrust creation can be explained on a one dimensional model [5]. The model yields an expression of thrust, depending on a current throughput, assuming that the electrode length is long compared to interelectrode distance and space charge effects are negligible. This holds at low current values.

Further assuming one dimensional homogeneous field between electrodes, the Force acting on a charge density ρ, expressed as

$$\rho = \frac{I}{A\mu E} \tag{1}$$

where A is the characteristic area perpendicular to x axis, μ stands for ion mobility and E for electric field intensity.

The force can be calculated as

$$F = \int_d \rho E A \mathrm{d}x = \frac{Id}{\mu} \tag{2}$$

where I is the current throughput and d electrode separation. Using current-voltage relationship for corona discharges, the thrust can also be expressed as a function of voltage

$$F = \frac{CV(V - V_0)d}{\mu} \tag{3}$$

where C is empirical constant, related to geometry and V_0 is corona inception voltage.

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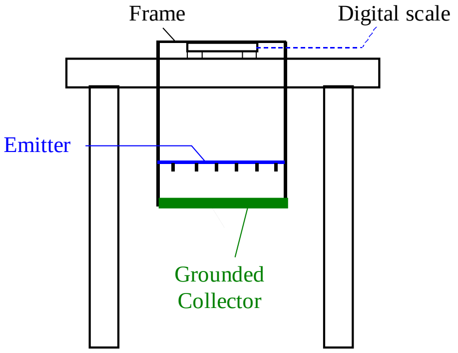

Fig. 1. Schematics of experimental set-up

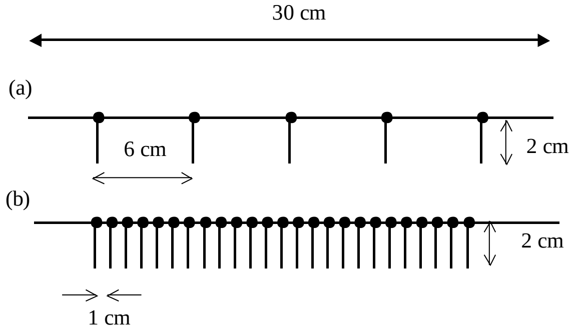

Fig. 2. (a) – emitter with 5 pins, (b) – emitter with 25 pins

3 EXPERIMENTAL SET–UP

Values of thrust were acquired by means of a digital scale, with accuracy of 0.02 g. Upward force, produced by the thruster electrodes mounted on a frame, resulted in a decrease in weight, measured by the digital scale. The set-up can be seen in the Fig. 1.

The grounded collector electrode is shown in gray, as it has been used just for two electrode experiments, done for comparison.

As a power source, TuR-WPT 4,4/100-GPT 6/125 in a grounded cage, has been used. The power source had maximum effective output voltage of 100 kV with a frequency of 50 Hz. Schematic figures of the two pin emitters used in the experiments are shown in Fig. 2

In all experiments with collector, gap length, measured from the emitter tips to the collector, has been kept constant at 13 cm and a collector with a diameter of 7 mm has been used.

The emitters and collector were easily demountable, thus allowing for rapid changes in geometry during the experiments. The current values were obtained by the FLUKE 289 multimeter.

4 THRUST MEASUREMENTS

Thrust-voltage characteristics were measured using the two emitters, shown in Fig. 2. Configurations with and without collector were tested under AC and pulsed DC excitation. Single electrode characteristics were acquired under AC excitation only. Comparison of characteristics with and without collector can be seen in Fig. 3, where Fac stands for thrust produced using AC supply, $Fdc+$ stands for thrust generated by positive current pulses, $Fdc-$ by negative pulses and the characteristic using just emitter, Fe, has been supplied with alternating current.

The pulsed DC characteristics show lower thrust than AC, due to lower power input caused by half-wave rectification. The thrust levels of the emitter with, and without collector, were comparable at lower voltages. To verify whether it applies also for other emitter geometries, thrust-voltage characteristic of the 25 pin emitter were acquired, this time with finer step at lower voltage levels. Comparison of the thrust-voltage characteristics of AC-driven 5 pin (F5e) and 25 (F25e) pin emitters with and without collector is shown in Fig. 4.

The characteristics of single emitter electrodes, marked black, show higher dependence on the geometrical factors of the emitter than characteristics with collector. Measured values of thrust for the single emitters at voltage levels around 10 kV are comparable with values of the configuration with collector. Repeated measurements showed that values differ by maximum of 0.4 mN at voltage levels below 20 kV, but they differ by up to 1 mN at higher voltages. For better visibility of the error bars, just values below 20 kV are shown in the Fig. 5.

It is interesting to point out that force-to-power (F/P) ratio of DC powered EHD thrusters is highest for low voltages and thrust values, which has been found by Masuyama [3]. However the same does not necessarily apply for AC driven thrusters.

As Fig. 6 shows, the measured thrust-to-power ratio of AC driven thrusters seem to be much lower than thrust-to-power of DC thrusters at low voltage levels.

The multimeter used, according to manufacturer, measures True RMS value, thus both capacitive character of the emitter-collector system and non-sinusoidal corona discharge characteristics should not influence the accuracy of the measurement. Repeated measurements show that AC thruster efficiency does not peak at low thrust values. The difference between DC characteristics at low voltages, is probably caused by higher uncertainty of measurement at low thrust values.

As shown in Fig. 4, thrust levels of single electrode thrusters are comparable to the configuration using collector at low voltage levels, suggesting higher thrust-to-weight ratio, due to lower weight. The comparison of thrust-to-weight ratio of single electrode and single stage thrusters can be seen in the figure below.

The major part of the weight of a single stage EHD thruster can be accounted to collector and support structure, holding emitter and collector at a constant distance. The weight of the emitter is usually negligible compared to the weight of the other parts. In our experiment, the emitter weight was 3.8 g and collector weight 6.8 g. The

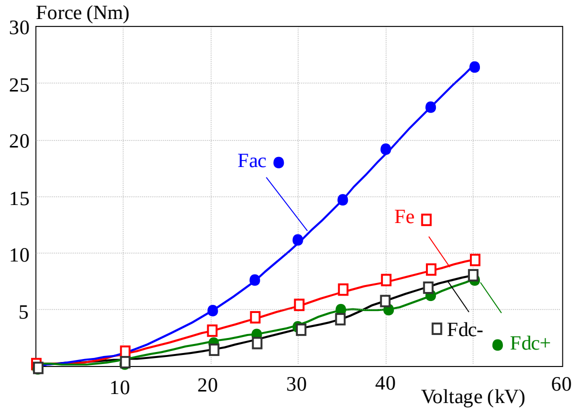

Fig. 3. Thrust-voltage characteristics using the 5 pin emitter

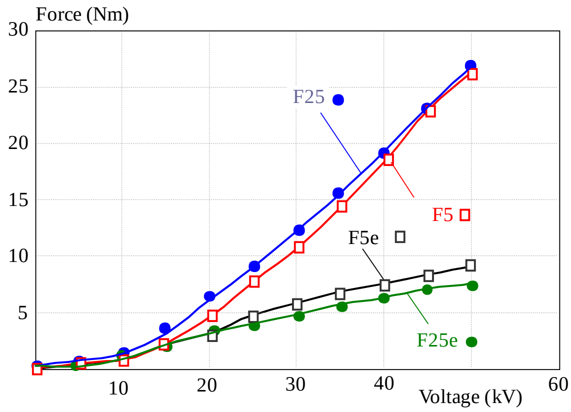

Fig. 4. Comparison of the thrust-voltage characteristics of the two emitters, with and without collector

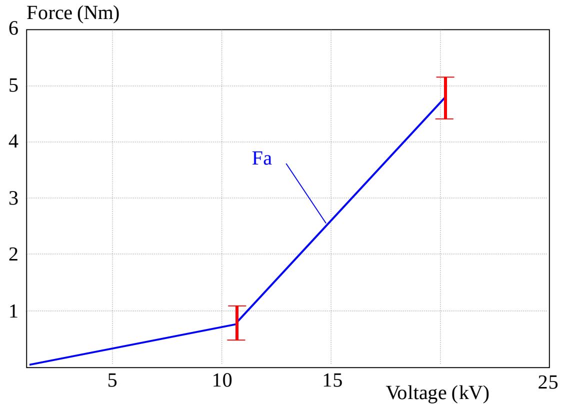

Fig. 5. Thrust-voltage characteristics of the AC-driven 5 pin emitter with collector

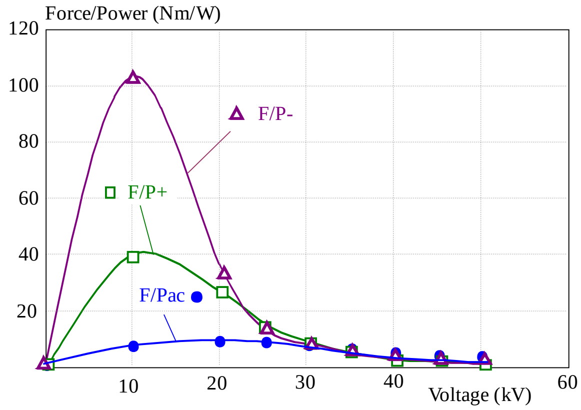

Fig. 6. Thrust-to-power voltage dependence of a single stage thruster with 5 pin emitter

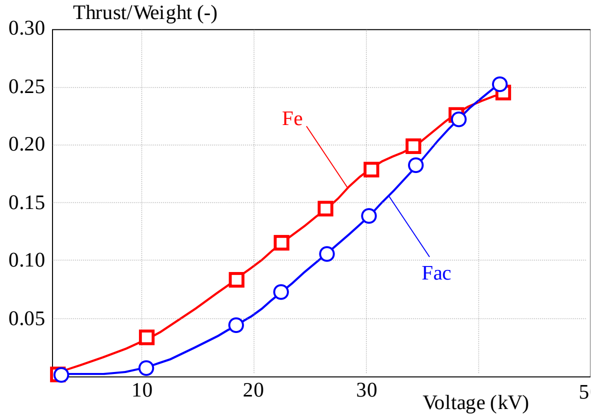

Fig. 7. Thrust-to-weight comparison of single emitter and single stage design with 5 pin emitter

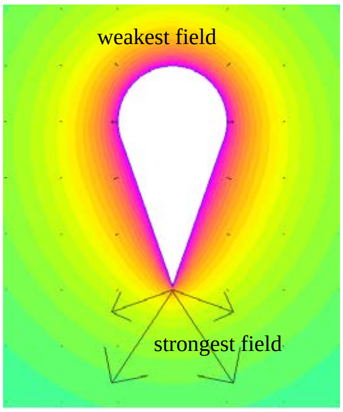

Fig. 8. Electric field around a sharp charged object

weight of emitter was not optimized for highest thrust-to-weight ratio, so further improvements are possible.

For aerial applications, the weight of the power supply and batteries will have to be considered.

5 DISCUSSION

To introduce the hypothesis of thrust creation by a single electrode thruster, let us first try to explain the thrust creation by a single stage EHD thruster under AC excitation.

The one-dimensional theory of EHD thrust assumes constant electric field. Despite that, measured AC characteristics followed the same quadratic voltage dependence as described by the theory.

To explain the match, we have to look again at the assumption of stationary electric field. If the time t_d required for the charged particle to travel the distance d between two electrodes is low compared to the duration of a single sine voltage impulse t_s,

$$t_d \ll t_s \tag{4}$$

the assumption of stationary electric field holds for the individual charged particles, travelling between the electrodes.

The estimate for time t_d, required for a charged particle, travelling at the drift velocity v_D4 to travel the distance d between two electrodes with a potential difference of V, can be expressed as

$$t_d = \frac{d}{v_D} = \frac{d}{\mu E} = \frac{d^2}{\mu V} \tag{5}$$

where μ is ion mobility. For ion mobility in the air at standard conditions for temperature and pressure (SATP) and voltages of tens of kilovolts, the values of t_d, assuming gap length, used in the experiments, are on the order of microseconds.

So the proposed explanation can be applied only at low frequencies, such as 50 Hz, used in our experiments.

If the gap length is too large, or frequency too high, the charged particles will not be able to reach collector electrode, before the change of the field polarity takes place. This is the case for a Tesla coil driven pinwheels, as well as for single electrode thrusters. For a given geometry, with increasing frequency, the condition (5) will be less and less satisfied. When the condition for quasi static field no longer holds, ponderomotive force, expressed as

$$F_P = -\frac{e^2}{4m\omega^2}\nabla E^2 \tag{6}$$

where e is particle charge, m particle weight, ω oscillation frequency of the field and E field strength, becomes the dominant mechanism of thrust creation. Ponderomotive force is present in inhomogeneous oscillating fields and acts on both positive and negative charges in the direction opposite to the gradient of the field [6].

If the field gradient around emitter was symmetrical, the ponderomotive force would have the same value in every direction, thus cancelling out and producing no net thrust. Net thrust can be observed just in case of spatially asymmetrical field gradient, which implies asymmetrical electrode, like the one in Fig. 8.

One of the reasons, why corona pinwheels always incorporate sharp end points, is that charge on the surface of objects, tends to concentrate in sharp points.

When the field intensity at the tip reaches critical intensity, a corona discharge is ignited. Because the field is weaker anywhere else on the surface of the object, there is a range of voltages, at which corona is confined to the tip region. This causes inhomogeneous ionization on the surface of the object with most ions created by corona discharge at the tip. In combination with higher field strength, the contribution of the tip region to total thrust is higher than that of the flatter region on the opposite site, thus producing net thrust.

6 CONCLUDING REMARKS

In this paper, we present thrust measurements and propose a hypothesis of thrust creation by a single electrode electrohydrodynamic thruster. Measured thrust values are shown in comparison with classical single stage design. Single electrode thrusters and single stage EHD thrusters of the same length and emitter geometry were found to produce comparable thrust at AC voltages around 10 kV. At such voltage levels, single electrode thrusters have higher thrust-to-weight ratio, due to low weight design. However, the efficiency under AC excitation in the mentioned voltage range is lower than the efficiency of DC powered thrusters.

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