Characterization of Corona Wind in a Modular Electrode Configuration

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***Abstract* -- Corona wind occurs when a high voltage above corona onset is applied to an electrode system. The ions generating the corona current impart their momentum to the near-by neutral molecules generating corona wind and propulsive forces on the asymmetric electrode generator. Various electro-hydrodynamic lifters were built but literature is scarce on corona wind electrode interaction. A modular corona wind generator was built and the thrust values were measured for the system. Positive high voltage is used at the stressed electrode system. The apparatus allows for systematic change in electrode configuration and comparison of the generated thrust. Data analysis has shown an inverse proportionality of the average thrust per coronating module with the number of modules used. While total thrust is increasing with applied voltage, it is also increasing with inter-modular distance. However, this rate of increase diminishes significantly for intermodule distance larger than 4 cm, showing less inter-electrode interaction. We hope our results may be useful in the design of modular corona systems aiming at optimizing corona wind thrust.**

I. INTRODUCTION

High voltage on a thin wire creates a very strong non-uniform field electric field. The field causes ions to be formed. As the ions are accelerated by the field they impart some momentum on the surrounding air molecules generating ionic wind or corona wind [1]. The speed of the flow is proportional to the corona current [2, 3]. Both positive and negative corona generates ionic wind. However, positive corona generates more momentum from the acceleration of positive ions [4, 5] with optimized winds [6] reported to reach 10 m/s [7] or more. Ionic wind can be described theoretically [4] and has been used for the manipulation of airflow around profiles [8]. For simulation analysis, a set of partial differential equations (1) coupled with Navier-Stokes and continuity equations are used

$$\nabla^2\Phi = -\frac{\rho}{\varepsilon};\quad \nabla\cdot(\rho\nabla) = 0 \qquad (1)$$

(Φ is the voltage potential; ρ is the charge density; ε is the dielectric permittivity of air).
Corona wind thrust can be employed for propulsion in air of light objects [4, 9-12]. In this case the phenomenon is called Brown-Biefeld effect [13], named after its discoverer. Although there is interest in harnessing the corona thrust, there is still a lack of systematic

study on the resulting forces according to the shape and overall design of the electrohydrodynamic lifters. A generally used structure/module in the design of such lifters consists of an asymmetric capacitor (Fig. 1a) made of a grounded rectangular aluminum foil (tinfoil) and a corona wire in the plane of the grounded electrode. Corona wind flow has been visualized for such structure [14] showing the airflow vortex formation. This module is at the core of such simple and more complex lifters. Nevertheless, little is known about the module interaction. We assumed that the thrust of a corona module as shown in Fig. 1a does not scale linearly with the number of modules in a more complex configuration. In order to qualify this hypothesis, an apparatus was designed with an array of 6 separate corona modules. The goal was to experimentally study such interaction for parallel corona modules which could potentially be used in the optimization of lifter design or associated applications.

II. EXPERIMENTAL

A. Experimental setup

The design of the corona modules is shown in Fig. 1a. Each separate module has a top 32 gauge wire (0.20 mm) that was attached to positive high voltage and a grounded 5 cm wide aluminum foil below the high voltage wire. The design allowed for the corona wire to be moved ½ cm between 5 different pre-drilled holes in the module insulating support. During all the experiments presented here a constant air gap distance of 2 cm was insured between the corona wire and grounded aluminum foil electrode.

A separate apparatus was designed for the study of corona module interaction. We arranged multiple modules in an array on a special support (Fig. 1a and Fig. 2). The apparatus allows us to change the spacing of the corona module array. The modules can easily be positioned parallel to each other at various inter-spaces. The insulating support is made partly from balsa wood allowing for a controlled distance between modules while keeping the modules parallel and aligned. The support allows each individual module to be moved /set on the support in either direction, with 1 cm spacing between notches.

A 0.01 g precision digital scale was placed under the entire apparatus in order to measure the change in weight caused by corona wind. The support holding the corona module array was designed to be tall enough so that it does not interfere with the proper functioning of the scale. It also had a flat surface on the bottom, shielding the scale from the corona wind.

The corona wire of each module was connected to the next corona wire using a white 40 kV high voltage cable. This was meant to allow for a variable distance between modules, minimizing errors associated to the inter-module high voltage connecting wires.

The positive high voltage was applied from a high voltage power supply Spellman, RHR40PN60 (positive 0-40 kV 1.5 mA).

B. Procedure

All experiments were performed at room temperature and atmospheric pressure. The apparatus was set on top of the digital scale. After adjusting the number of modules and inter-module distance to the desired values, and after zeroing the scale, a positive high voltage was applied to corona modules. Voltage was slowly increased, monitoring the value displayed on the scale. Once corona wind starts, the scale would read negative values, indicating the change in relative weight of the entire apparatus. Data were recorded and the lifting force calculated and plotted versus voltage. Measurements were stopped when air breakdown happened. Different arrangements meant to reveal module interaction within the corona wind apparatus were prepared and data were colected as presented.

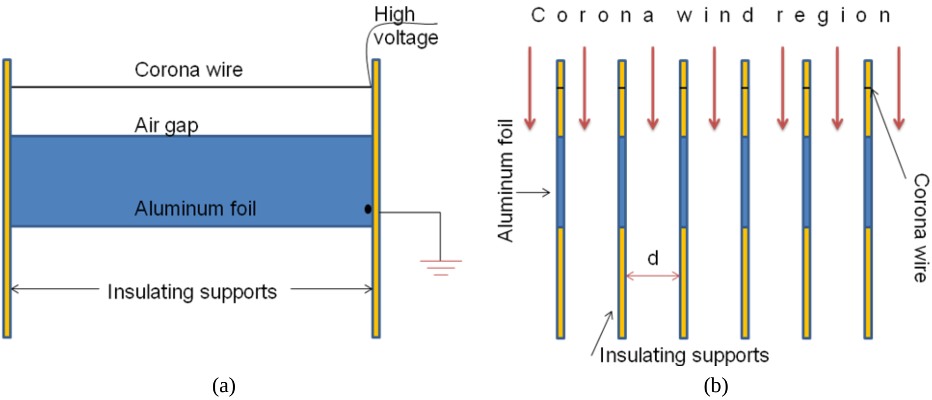


Fig. 1 Schematics of the experimental setup. (a) Asymmetric capacitor module: corona wire was attached to the positive high voltage, 2cm below a 5 cm wide aluminum foil electrode (b) Side view of 6 asymmetric capacitor modules.

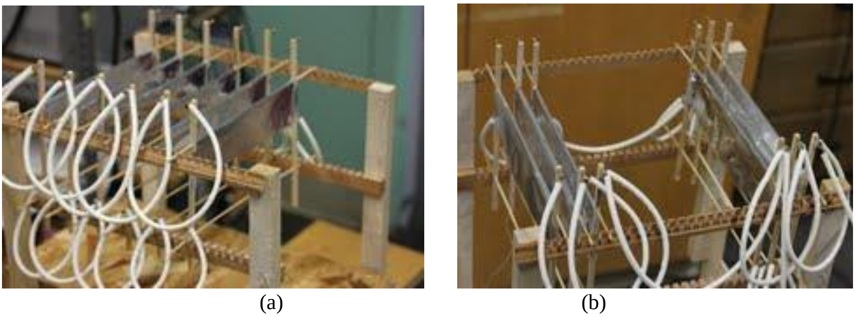


Fig.2 Experimental apparatus: (a) equally inter-spaced corona modules; (b) the photo shows how the high voltage connections allow for variable inter-module distance: the modules are electrically interconnected with white high voltage cables.

C. Results and analysis

The readings of the raw data from the scale were converted to force units. Setting the number of corona modules to 6, the inter-module spacing was varied from 1 cm to 6 cm (as mush as it was available on the built apparatus). Fig. 3 shows the plot of the average lifting force from two data sets versus the applied voltage. The lifting force is found in empirical studies to be proportional to corona current and it can also be derived theoretically [4] so that:

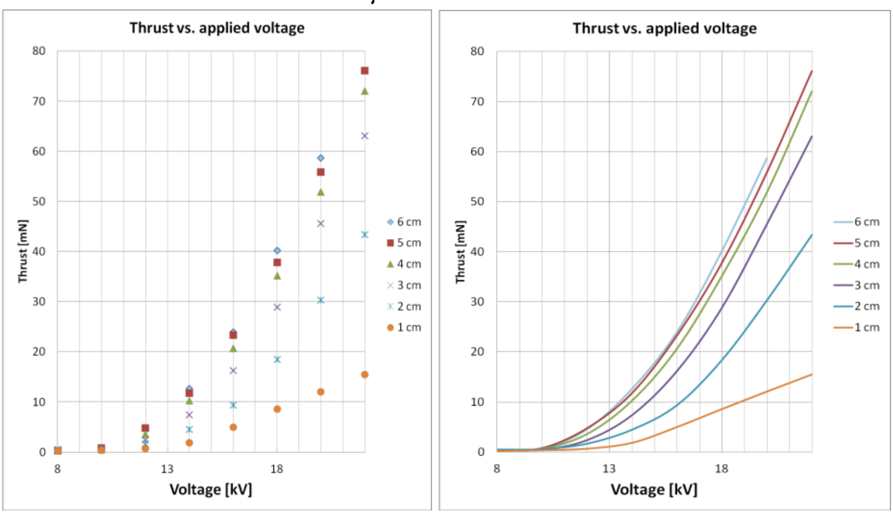
$$F = I\frac{ka}{\mu} \qquad (2)$$

where “I” is the corona current, “a” is the distance between the corona wire and the ground electrode, “k” is a constant of proportionality, while μ is the average mobility of ions. Corona current is generally accepted to follow a quadratic variation with the voltage above the corona onset [15 p. 261]

$$I = KV(V - V_o) \qquad (3)$$

where V_0 stands for corona onset voltage and K is a proportionality constant depending on electrode geometry. Therefore from (2) and (3) the lifting force should follow a quadratic variation with the applied voltage:

$$F = K\frac{ka}{\mu}V(V - V_o)\,. \qquad (4)$$



(a) (b)

Fig.4 Variation of the thrust with applied voltage: (a) experimental values (b) smooth line chart.

As shown in the chart, the force becomes noticeable only at about 10 kV, and then increases rapidly -- only to some degree according to a predicted shape coresponding to equation (4). As the distance beween modules increases, the force-voltage curves shift up to larger force values within the observed range. Measuring the force was limited by the voltage breakdown values, which in our laboratory setup and conditions was around 22 kV. Nevertheless, as intermodule distance increases, the curves shift to higher values less and less, with the curves at 5 cm and 6 cm almost overlapping. Force variation with inter-electrode distance at different voltages is shown in Fig. 5. The curves flatten with distance. The curves at 12 kV and 14 kV may have larger errors as corona is not a steady state phenomenon and forces are rather small at these voltages.

Wind speed and lifting force are dependent on module configuration. We measured the corona wind lifting forces for a different configuration shown in Fig. 2b having 3 modules interspaced at 2 cm and another 3 modules also interspaced at 2 cm. The force-voltage curve obtained was slightly below all the curves in Fig. 2. This would actually point to the presence of an optimum inter-module distance for achieving maximum thrust. Nevertheless, the dimensions of the current apparatus have prevented us at this time from expending measurements beyond 6 cm intermodule distance.

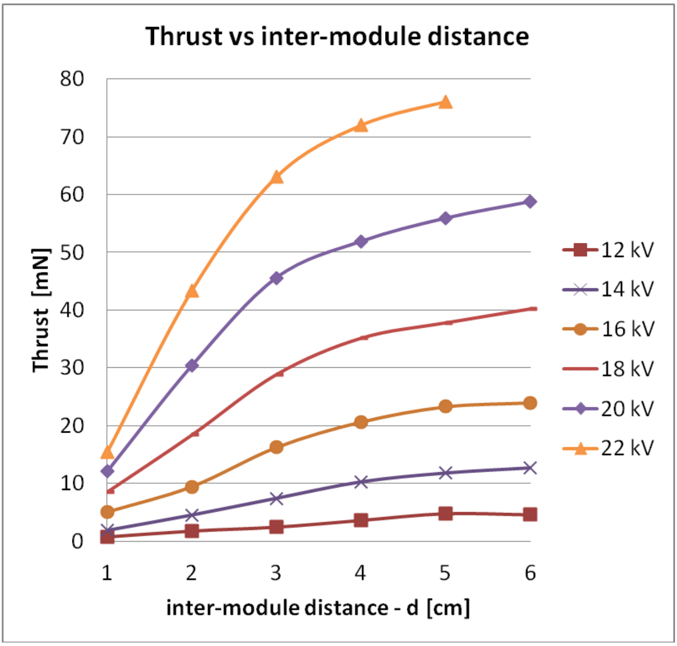
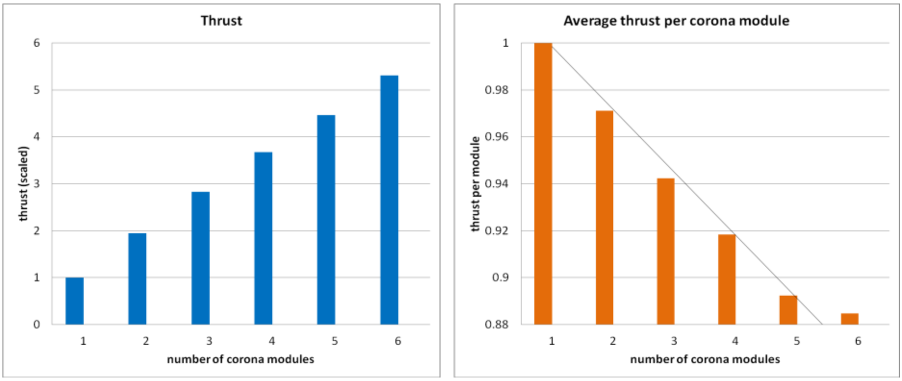


Fig. 5 Thurst variation with inter-module distance at constant applied voltage.

Module interaction was probed in a different manner by varying the number of modules generating corona wind at one time. If there is no interaction between modules, the thrust generated by all modules should be multiples of the thrust generated by an independent module alone. In order to test module interaction, an equidistant arrangement of 6 modules was prepared with an interspace of d=6cm. At this interspace the thrust generated was the greatest in our measurements (the interspace could not be increased due to the apparatus's current design limitations). The thrust was measured at 16 kV (about midrange voltage where corona wind could be observed). Gradually, one module was removed at a time and the associated thrust was measured again. The process was repeated and the results are shown in Fig. 6.

The thrust does increase fairly linearly with the number of active corona modules. However, the increase, when using 6 modules, only adds up to 5.3 the thrust corresponding to an independent module (Fig. 6a). Fig. 6b shows the average thrust per module as it changes with the number of active corona modules. It is noticeable that an almost linear decrease in the added force per module is recorded up to a number of 5 modules. However, this linearity may not continue, as suggested by the last data point for 6 modules. The data is currently limited, as our experimental study only employes up to 6 modules.



(a) (b)

Fig. 6 (a) Scaled thrust variation with the number of active corona modules employed (the unit thrust is for a single independent module, voltage is +16 kV, and d=6cm – inte-rmodul distance); (b) Variation of the average thrust per module (scaled) with the number of modules employed.

III. CONCLUSION

An apparatus was designed with the purpose of testing and characterizing the interaction of a parallel corona module array. Different module configurations were implemented and the resulting thrust values were measured and compared. Only positive corona was employed as it provides more momentum than negative corona. The experimental results and analysis demonstrate that interaction between corona modules does take place. For the 1 cm inter-module distance the generated corona wind thrust values are the smallest (most interaction) while for the 6 cm inter-space they are the largest (least interaction). For the range we experimentally explored, corona wind thrust (keeping the voltage constant) tends to flatten out with the increase in inter-module distance. The average thrust per active module decreases with the number of modules, confirming the complex electrohydrodynamic interaction in the system. Our study, although limited by the dimensions of our experimental apparatus, demonstrates that optimizing corona thrust is essentially linked to controlling inter-modular distance, besides the usual parameters needed for an independent module.

IV. ACKNOWLEDGMENTS

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