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Altitude dependence of electrohydrodynamic flow in an electrostatic lifter

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ABSTRACT

Experiments carried out during the last 50 years have elucidated the basic mechanism of the Biefeld-Brown effect. Recent research has focused on establishing design rules in order to maximize the lifting force resulting from this effect. For this purpose, a numerical estimation that takes the effect of altitude into account is needed. In the present contribution, the thrust due to Biefeld-Brown effect was computed by simulating the corona-discharge-induced electrohydrodynamic flow in a widely used high-voltage asymmetric capacitor with the major goal to elucidate the dependence of thrust on the altitude, pressure, temperature and humidity, respectively. Our numerical results reproduced the experimentally observed decrease of thrust with altitude and shown that this is a consequence of various competing effects.

1. Introduction

The Biefeld-Brown effect (BBE) named after Paul Biefeld and Thomas Townsend Brown supposed to discover this by working together, has its original description from the late 1920s almost exclusively given in patent claims by T. T. Brown [1], or provided by "pseudo-scientific" articles in popular magazines, such as Ref. [2]. Due to the bombastic titles of the patent claims by T. T. Brown introducing the Biefeld-Brown effect (BBE) and the speculations that BBE could couple the electromagnetism and gravitation, it is not at all surprising that over the years BBE got an esoteric touch. Nevertheless, stipulated by the Breakthrough Propulsion Physics Project funded by NASA from 1996 through 2002 [3], an intensive hype resulted in BBE too in the late nineties, leading beyond to its rediscovery also to further patent claims [4].

Compendiously, BBE is that effect which yields a thrust in a high-voltage asymmetric capacitor. Already in 1967, it was experimentally shown that the corona discharge ("ionic wind") phenomena can explain BBE because it can generate a pressure and/or velocity gradient within the dielectric fluid, e.g., air, separating the electrodes [5]. Since 2003, it is also clear that rather the ionic drift between the electrodes than the ballistic transport of ions is the leading mechanism which could quantitatively explain the magnitude of the thrust [6]. More recently, it was experimentally reconfirmed both the existence and the ionic origin of the air flow between the electrodes [7]. In another recent experimental paper [8], even a couple of design rules for the high-voltage asymmetric capacitor were suggested, which seem to maximize the resulting lifting force. However, it was already concluded that the corona discharge, i.e., the ionic wind, cannot be used for aircraft propulsion [9].

In spite of all experimental knowledge gained so far, still does not exist an all-purpose theoretical description of BBE cf., for example, the electrostatic approach of Ref. [10] with the aerodynamic model used in Ref. [11]. The main reason for this lies in the complexity of the corona discharge phenomena [12]. Therefore, in the present contribution, the thrust due to BBE was computed by simulating the corona-discharge-induced electrohydrodynamic (EHD) flow [13] in a widely used model high-voltage asymmetric capacitor formed by two wires of circular and wing profile, respectively, with the major goal to numerically verify the validity of some known empirical formulas for the thrust and also to elucidate the dependence of thrust on the altitude, pressure, temperature and humidity — not yet investigated in the literature.

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2. Electrohydrodynamic flow

The phenomenon of the corona-induced ionic wind is known for many decades, see for a review Ref. [14], and it shows up in general, when an electric potential difference is applied to a pair of electrodes having different curvatures. Due to this difference in curvature, the electric field in the region around the corona electrode of small curvature will be higher than that around the collector electrode with a large curvature. Therefore, if the electric potential difference is high enough, the air molecules surrounding the corona electrode will ionize in a process known as electron avalanche. These ions are then attracted by the collector via the Coulomb's force acting on them. In their travelling towards the collector, the ions collide with neutral molecules transferring their momentum and producing the ionic wind. By Newton's Third Law, the force downwards creates an equal, opposite force which pushes then the capacitor upwards. This ionic wind is commonly also known as electrohydrodynamic (EHD) flow.

The gap between the corona and collector electrode can be divided into two regions: one, where the ionization of the air molecules takes place and another one, where the ionic drift occurs. As long as the ionization zone is situated in close proximity to the corona electrode, the drift zone comprises the region outside this, where the neutral and charged particles drift towards the collector electrode. From the description of the EHD flow in the literature [13,15–18], it is possible to distinguish three different physical phenomena contributing to the ionic drift: an electric field produced by the electric potential difference between the electrodes, an electric current resulting from the movement of the charged particles, and the movement of the neutral air particles as a consequence of their collision with charged particles.

Accordingly, the governing equations are as follows. The electric field $\mathbf{E}$ imposed by the electric potential V is given by

$$\mathbf{E} = -\nabla V \,, \tag{1}$$

where as the induced space charge density ρ is determined by Poisson's equation,

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0 \varepsilon_r} \,, \tag{2}$$

with ε_0 being the dielectric function (permittivity) of free space, and ε_r is the relative permittivity of the dielectric medium, e.g., the air in our case.

The total electric current density $\mathbf{J}$ is written as

$$\mathbf{J} = \mu_{\mathrm{E}} \mathbf{E} \rho + \mathbf{U} \rho - D \nabla \rho \,, \tag{3}$$

where μ_{E} is the ion mobility in the dielectric medium, here air, $\mathbf{U}$ is the airflow velocity vector, and D is the ion diffusion coefficient. The first, second and third term in this Eq. (3) correspond to the conduction, convection and diffusion, respectively. Since we assume that no ions are formed in the drift zone, the steady-state electric current density $\mathbf{J}$ obeys the continuity equation,

$$\nabla \cdot \mathbf{J} = 0 \,. \tag{4}$$

As it will be later shown, under the conditions considered in this study, the pressure arising during the EHD flow towards the collector electrode, is low enough to have the dielectric medium incompressible. Consequently, in the steady state, the dynamic of the fluid is described by the Navier-Stokes equation taken for external electric force $-\rho\nabla V$, i.e.,

$$\rho_{\mathrm{air}} \mathbf{U} \cdot \nabla \mathbf{U} = -\nabla p + \eta \nabla^2 \mathbf{U} - \rho \nabla V \,, \tag{5}$$

and the corresponding continuity equation

$$\nabla \cdot \mathbf{U} = 0 \,, \tag{6}$$

where ρ_{air} is the air density, p is the air pressure, and η is the dynamic viscosity of air.

3. Computational details

To describe the EHD flow, one has to solve the governing equations given in the previous Sect. 2, which constitute a set of coupled nonlinear differential equations. Consequently, analytical solutions can be obtained only for systems with relatively simple geometries [19]. Some numerical solutions have been developed to tackle this problem [19], however, many of them involve approximations that neglect some of the physics involved. During the last decade, the finite element method (FEM) has proven to be a useful tool in modeling EHD flow for arbitrary geometries [13–16,20], and therefore it was selected to carry out this computational study too. To this end, the commercial software package COMSOL Multiphysics 5.0 was employed [21], which performs equation-based modeling for different physical processes by applying FEM techniques.

The solution of Eqs. (1)–(6) is carried out via a time instantaneous fully coupled approach. The solution of the resulting system of equations uses an affine invariant form of the damped Newton method as described in Ref. [22].

3.1. Setup of a model capacitor

We considered a configuration of a model capacitor consisting of a circular corona wire electrode placed above a circular collector electrode and separated by an air gap from it. The projections of these electrodes in the plane perpendicular to the symmetry axis of the cylinder, i.e., z-axis in Fig. 1, are concentric circles of identical radii. The dimensions of the objects composing this model system are detailed in Table 1. Since this model system exhibits axisymmetry, only one plane is explicitly modeled, recall Fig. 1, and the proper symmetry transformations are applied to recover the original 3D configuration. The electrodes were enclosed inside a large domain employed to model a finite surrounding air volume. This volume was determined by increasing its size in finite steps until convergence of the solution was achieved.

To solve Eqs. (1) and (2) for the given geometry, the Electrostatics COMSOL module was employed [21]. This module treats the electric potential as independent variable and handles the axisymmetry condition automatically. The electric potential should obey the physical restriction of vanishing at infinity. It is not possible, however, to construct a domain of infinite size around the electrodes. Since the electric potential decays as $1/r$, it suffices in practice to construct a large domain, where one expects a numerically small value of the potential at the boundaries. This value can be approximated as zero without introducing large errors in the computation of the electric potential. Based on this, a ground electric potential ($V = 0$) was applied at the boundaries of the enclosing box and on the surface of the collector electrode, while a finite potential V_e was imposed on the corona electrode. Finally, Eqs. (1) and (2) were solved on the domain corresponding to the air volume surrounding the electrodes as depicted in Fig. 1.