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Optimization of micro single dielectric barrier discharge plasma actuator models based on experimental velocity and body force fields

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ABSTRACT

Recently, the Micro Single Dielectric Barrier Discharge Plasma Actuator has become attractive for application in aeronautics and micropopulsion thrusters. The present work carried out a preliminary characterization of such device, acting on initially quiescent air by experimental and numerical approaches. Sinusoidal voltage excitation with amplitude up to 7 kV and frequency up to 2.5 kHz was applied. The induced flow was investigated by particle image velocimetry and the measured velocity fields were used to estimate experimentally the time-averaged induced body force distributions by a differential method. Plasma induced forces were modeled by following three different approaches, later implemented as a source term in the Navier–Stokes equations for the fluid flow simulations. Potentialities, advantages and disadvantages of the considered force modeling methods were investigated. Quantitative comparison of the experimental and numerical induced force, as well as of the velocity fields, allowed establishing which model best predicted the actuator effects. The algebraic Dual Potential Model provided a good agreement between experimental and simulated results, in terms of flow velocities and thickness of the induced wall-jet. The downstream decay of the wall-jet velocity, experimentally observed, was also successfully predicted. A maximum induced velocity of ≈2 m/s was obtained and a jet thickness of ≈3 mm.

1. Introduction

In recent years, single dielectric barrier discharge (SDBD) plasma actuators have gained great interest among all the active flow control devices typically employed in aerospace applications [1,2] as they offer several major practical advantages: they require low power consumption, involve no moving mechanical parts, are relatively easy and inexpensive to construct, implement and repair, are lightweight and have a very high frequency response allowing real-time control [3,4]. Owing to these features they are very attractive in aeronautics for reattaching separated flows [3,5,6] or controlling the boundary layer transition to turbulence [7–9], but also for reducing the aircraft noise [10]. Novel usages of the SDBDs are also on the field of micropopulsion for space and stratospheric altitude applications. The SDBD powered microthrusters, like the Free Molecular Electro Jets (FMEJs), have been proposed and investigated to provide control authority for small satellites in orbits and high altitude gliders, requiring forces of the order of several microNewtons or less for executing various maneuvers [11–13].

SDBD plasma actuators: A SDBD consists of an asymmetric pair of metallic electrodes separated by a dielectric

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Nomenclature

H	harmonic mean
$\mathbf{E}$	electric field vector (V/m)
$\mathbf{F_b}$	plasma-induced body force per unit volume vector (N/m^3)
$\mathbf{f_b}$	plasma-induced mean body force per unit volume vector (N/m^3)
$\mathbf{n}$	surface normal vector
$\mathbf{v}$	velocity vector $\mathbf{v}=(v_x, v_y)$ (m/s
$\hat{f}$	applied voltage frequency (Hz) or (kHz)
g	electrode gap size (m) or (mm)
l	electrodes spanwise length (m) or (mm)
p	pressure (Pa)
t	time instant (s) or (ms)
t_k	dielectric material thickness (m) or (mm)
x, y	cartesian coordinates (m) or (mm)
$y_{1/2}$	y coordinate corresponding to $v_x = 1/2 v_{x,max}$ (m) or (mm)
F_b	plasma-induced body force per unit volume magnitude (N/m^3)
f_b	time-averaged plasma-induced body force per unit volume magnitude (N/m^3)
v	time-averaged velocity magnitude (m/s)

Dimensionless numbers

Co	Courant number
N	dimensionless number expressing the inertial effects in the response of viscous and viscoelastic fluids to a stress propagation
$Re_{y_{1/2}}$	Reynolds number based on the maximum velocity $v_{x,max}$ and $y = y_{1/2}$

Greek symbols

δ	penetration depth of an oscillatory disturbance at frequency $\hat{f}$ (m) or (mm)
ϵ	permittivity $\epsilon = \epsilon_r \epsilon_0$ (F/m)
ϵ_0	permittivity of the free space (F/m)
ϵ_r	relative permittivity of the medium
$\hat{\phi}$	amplitude of the potential applied on the exposed electrode (V) or (kV)
$\hat{\rho}_c$	maximum value of the net charge density allowed in the domain (C/m)
λ_d	Debye length (m)
μ	air dynamic viscosity (Pa s)
ω	vorticity (1/s)
Φ	electric potential (V) or (kV)
ϕ	potential due to the external electric field, caused by the voltage applied to the electrodes (V) or (kV)
ρ	air density (kg/m^3)
ρ_c	net charge density in the fluid domain (C/m)
$\rho_{c,w}$	net charge density on the surface of the dielectric over the embedded electrode (C/m)
φ	potential due to the net charge density in the plasma (V) or (kV)

Subscripts

ar	air
$FR4$	glass reinforced epoxy laminate
max	maximum
min	minimum
PG	Plexiglass
x, y	cartesian component

material: one of the electrodes is grounded and embedded in an insulating material, while the other one is exposed to the surrounding fluid and connected to a high-voltage excitation. The conventional SDBD operating mode involves the application of an alternating current (AC) voltage with amplitude in the kV range and frequency in the kHz range (with or without modulation or pulsing), which causes the gas near the plasma actuator to weakly ionize. The interaction of the electric field with the charged particles in the plasma originates an electrohydrodynamic (EHD) body force on the surrounding gas – neutrally charged – inducing a wall jet of few m/s occurring at few millimiters above the dielectric surface [14]. While in aeronautical applications the SDBDs are flush-mounted over the aircraft wings or on the suction side of the low pressure turbine blades, the FMEJ microthruster application involves embedding the SDBDs along the dielectric surface of its channel walls to impart momentum to the propellant in a desired direction, by the appropriate design and placement of the electrodes [11]. The SDBDs commonly denominated as “typical” are generally characterized by an electrode width in the order of centimetres [3,15,16]. A SBDB characterized by an electrode width less than 4 mm [17] and electrode thickness, dielectric thickness and electrodes gap in the micrometric scale, is instead defined as micro SDBD (hereafter noted as ”MSDBD”). The MSDBDs could address the control in precise flow locations [18] with lower power consumption and intrusiveness and provide opportunities for controlling the small-scale structures in macroscopic turbulent flows [17]. Furthermore, small and thin devices can be located anywhere on the control surface and a correct dielectric material choice implies durable and efficient devices that easily conform to surface curvature, with a consequent simple integration and minimum impact in the model. Farther these advantages, literature works studies [17,19,20,21] demonstrated also that the MSDBD adoption brings to an increase of the actuator efficiency in converting input electrical power to delivered mechanical power and of the induced force and velocity per unit actuator mass. The higher thrust per weight performance with respect to the “typical” SDBDs is a major attractive feature for using MSDBDs in applications where weight penalty is important, as in small satellites and lightweight high-altitude gliders microthrusters [11]. In spite of all these benefits, unlike for “typical” SDBDs [3,6,15,16], there is still not a wide literature study about MSDBDs.