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Heat generation mechanisms of DBD plasma actuators

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ABSTRACT

During the last twenty years DBD plasma actuators have been known by their ability for boundary layer flow control applications. However, their usefulness is not limited to this application field, they also present great utility for applications within the field of heat transfer, such as a way to improve the aerodynamic efficiency of film cooling of gas turbine blades, or de-icing and ice formation prevention. Nevertheless, there is a relative lack of information about DBD's thermal characteristics and its heat generation mechanisms. This happens due to the extremely high electric fields in the plasma region and consequent impossibility of applying intrusive measurement techniques. Against this background, this work describes the physical mechanisms behind the generation of heat associated to the DBD plasma actuators operation. An experimental technique, based on calorimetric principles, was devised in order to quantify the heat energy generated during the plasma actuators operation. The influence of the dielectric thickness, as well as the dielectric material, were also evaluated during this work. The results were exposed and discussed with the purpose of a better understanding of the heat generation mechanisms behind the operation of DBD plasma actuators.

1. Introduction

In recent years DBD plasma actuators have been a subject of interest for the worldwide scientific community [1–3]. Several studies have demonstrated the potential of these actuators in separation control [4], wake control [5,6], aircraft noise reduction [7], modification of velocity fluctuations [8,9], and boundary layer control [10–13]. These devices have very attractive features including a very low mass, low power consumption, fast response time, being fully electronic and not presenting moving mechanical parts. Nowadays, they can even be simulated with different numerical solvers [14–20]. DBD plasma actuators are constituted by two electrodes separated by a dielectric layer (Fig. 1). One of the electrodes is covered by the dielectric layer and is completely insulated from the other one, that is exposed to the air in the top of the dielectric. Thus, the electrodes are, respectively, designated as the covered electrode and the exposed electrode [21–23]. To operate a DBD plasma actuator the two electrodes should be connected to an AC high voltage and high frequency power supply. When the amplitude of the voltage applied to the exposed electrode is large enough, ionization of the air (plasma) occurs over the surface of the dielectric, which in the presence of the electric field gradient produces a body force on the ambient air. Thus, the actuator induces a flow that draws air towards the surface of the actuator, and it accelerates this air downstream in a direction tangential to the dielectric [24–27].

Although the main applications of DBD plasma actuators are related to the field of flow control, these devices have also possible applications in the field of heat transfer, such as film cooling of turbine blades and heat generation for de-icing, or ice formation prevention. Some studies have already been conducted showing film cooling enhancement obtained by the operation of plasma actuators. Roy and Wang [28] numerically tested a plasma actuator for film cooling enhancement on a flat plate, while Yu et al. [29] studied film cooling performance for a cylindrical hole with plasma aerodynamic actuation. These studies demonstrated that plasma actuators allow to improve the film cooling effectiveness. However, the heat dissipated during the plasma actuators operation affects negatively the film cooling performance. To improve the plasma actuators performance, in film cooling applications, it is strictly necessary to understand the heat generation mechanisms behind their operation. Later the heat generation can be reduced in order to optimize the film cooling effectiveness. Regarding de-icing, or anti-icing applications, two recent studies were performed. In the work conducted by Meng et al. [30], the effects of plasma actuation on de-icing and anti-icing were studied by surface temperature measurements in quiescent air and icing wind tunnel, whereas in the study of Van den Broecke [31], nano second DBD plasma actuators were used for de-icing purposes. Both studies showed that plasma actuators are effective in de-icing and anti-icing applications. Conversely to film cooling applications, for de-icing and anti-icing purposes the objective is to increase

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Nomenclature

ΔT	temperature variation
$\dot{m}$	mass flow rate
ϵ_0	vacuum permittivity
ϵ_R	relative permittivity
κ	thermal conductivity
ϕ	air flow rate
ρ	density
A	area
C_p	specific heat at constant pressure
d	dielectric thickness
f	frequency
I_a	current trough the actuator
I_r	current trough the resistor
m	mass
P_D	power converted in dielectric heating
P_T	thermal power
Q	calorific energy
R	resistance
U	voltage
U_r	voltage across the resistor

the heat generated during the plasma actuators operation and, consequently, optimize the de-icing process. For this purpose it is first necessary to understand the heat generation mechanisms present in the plasma actuation.

Despite of the importance of plasma actuators for applications within the heat transfer field currently the thermal characteristics of DBDs are not completely known, as a result of the complex nature of plasma formation, which makes difficult the measurement of the various parameters involved. According to Tirumala et al. [32] due to the extremely high electric fields in the plasma region, and the impossibility of applying intrusive measurement techniques, the two measurement techniques that can be used are infra-red thermography and emission spectroscopy. However, in the present paper, we will present an alternative integral experimental technique which makes possible to quantify the fraction of power dissipated as heat.

Still there have been studies carried out to better understand the thermal behaviour of DBD plasma actuators. Roth et al. [33] conducted a study where they presented data on the physics and phenomenology of plasma actuators. They explained that the power consumed by plasma actuators is composed of the power dissipated by the surface discharge and the thermal dielectric losses. They estimated the power losses in a plasma actuator considering that the power losses in the dielectric increase linearly with the voltage frequency and also with the square of the voltage amplitude. The principle used to determine the thermal power dissipated in the dielectric, presented in the Roth's study, will be also used in the present work. However, we will also verify that this thermal power is just a small portion of the total thermal power released during the actuators operation. Dong et al. [34] measured the influence of the frequency and applied voltage level on the dissipated power. They used an empirical formula, similar to the formula used by Roth et al. [33], to estimate the dissipated power and the energy loss in the dielectric. Plasma temperatures were also evaluated using spectroscopy emission measurements. The electrical power was measured for two dielectrics, epoxy and Teflon, for different thicknesses of the dielectric, and under various operating conditions (applied voltages and frequencies). They found that most of the active power is injected in the plasma, however, a large part of the remaining active power is directly transferred into the dielectric panel. Stanfield et al. [35] also conducted spectroscopy measurements of a DBD actuator in order to obtain the rotational temperature of the gas above the grounded electrode. They observed that the rotational temperatures of

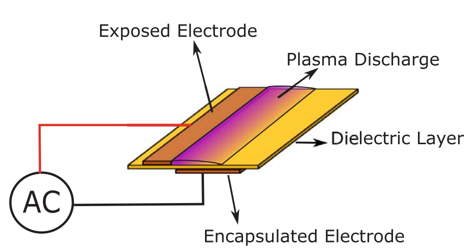

Fig. 1. Schematic of dielectric barrier discharge configuration.

the gas decreased in the induced flow direction and increased with increasing voltage. Jukes et al. [36] observed the temporal and spatial structure of the plasma actuator induced flow. They used thermal imagery to estimate the surface temperature of the dielectric sheet, during plasma operation, and deduced an analytical formula to estimate the plasma gas temperature. Later on, Joussot et al. [37] performed a study where they used the Jukess analytical formula and concluded that this formula is not accurate enough to estimate the plasma gas temperature. In Jussot's study [37] the authors used infrared thermography to determine the temperature of the dielectric surface with the plasma on, and after switching off the discharge. They concluded that the average surface temperature increased linearly with the electrical power, as it increased with the frequency and with the square of the voltage amplitude. The work performed by Erfani et al. [38] focused on the effect of actuator surface temperature and its aerodynamic performance. They conducted experiments with DBD plasma actuators applied in a surface at different temperatures (ambient temperature, −40 °C and 120 °C). The authors found that in a hotter actuator surface its possible to achieve higher velocities and higher body forces by consuming a slightly higher power. Tirumala et al. [32] also conducted infra-red thermography measurements on the surface of a thick, dielectric based, DBD actuator and characterized it against various electrical and geometrical parameters. They studied the temperature distribution and proposed an hypothesis on the mechanism of dielectric heating and a relationship between dielectric surface temperature and gas temperature. Aberoumand et al. [39] numerically studied the impact of different arrangements of dielectric barrier discharge plasma actuators on temperature field in a channel flow. The actuators were tested under an incompressible flow regime with a constant entrance Reynolds number. The authors verified the importance of heat generated by DBD plasma actuators operation and concluded that plasma actuators can be considered as beneficial instruments for increasing the temperature of the fluid. Furthermore, the authors have evidenced that the increase in temperature can be considerable and noted for related applications.

Recently Benmoussa et al. [40] conducted numerical investigations of the gas heating phenomenon in dielectric barrier discharges due to the joule heating effect for Ne-Xe gas mixtures. They observed that the gas temperature, close to the vicinity of the actuator, increase due to the high values of the power deposited in this region. They tested two different waveform shapes and showed that the gas temperature in DBD excited with rectangular applied voltage waveform reached higher values than with the discharge created by a sinusoidal excitation. Rodrigues et al. [41] conducted surface temperature measurements on actuators with different dielectric thicknesses and different dielectric materials under quiescent conditions. They verified that the temperature distribution is similar for the different test cases however the temperature levels change with the dielectric thickness and also with the type of dielectric material.

Further information can be found in the reviews of Bernard and Moreau [24] and Kotsonis [42] which compile the most relevant findings about DBD plasma actuators.