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Technical Notes

Effect of Relative Humidity on Dielectric Barrier Discharge Plasma Actuator Body Force

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Nomenclature

$\boldsymbol{E}$	=	electric field
$\boldsymbol{F}_B$	=	actuator body force
P	=	pressure
P_{SAT}	=	saturated water vapor pressure
P_V	=	partial pressure of water vapor
T	=	reactive thrust
T_{DRY}	=	reactive thrust for RH < 40%
V_{PP}	=	peak-to-peak applied voltage
RH	=	relative humidity
ρ	=	moist air density
ρ_C	=	charge density
ρ_{dry}	=	dry air density

I. Introduction

THE efficacy of dielectric barrier discharge (DBD) plasma actuators for aerodynamic flow control has been demonstrated in numerous studies as described in recent reviews on the subject by Corke et al. [1,2] and Moreau [3]. Most studies have been performed under well-controlled laboratory environmental conditions. However, application of these devices for active flow control on aircraft will require their effective operation over a wide range of climate conditions. Because the aerodynamic benefit of the devices is increasingly well (if not completely) understood, it is timely to investigate and characterize environmental influences that could potentially limit their utility. This Note focuses on the influence of ambient relative humidity (RH) on the body force produced by DBD plasma actuators. Although it is generally recognized that the efficacy of DBD actuators is reduced with increased relative humidity, the functional variation of actuator reactive thrust (a quantity directly proportional to body force) with relative humidity needs to be quantified. Determination of the functional variation of the body force with relative humidity would enable the development of DBD actuator compensator circuits for use on aircraft.

There have been previous efforts to assess the influence of relative humidity on DBD actuator performance. Anderson and Roy [4] reported preliminary experiments assessing the effect of relative humidity on the surface pressure coefficient over the somewhat narrow range of $43\% \le \mathrm{RH} \le 53\%$. They suggested a modest increase in actuator performance with relative humidity. A more recent study was reported by Benard et al. [5] over a wider range of $40\% \le \mathrm{RH} \le 98\%$. The actuator used a sinusoidal ac frequency of 1 kHz and voltage amplitudes from 16 to 24 kV. Although the results showed that DBD actuators can be operated at high RH, the measured plasma-induced wall jet velocity was clearly reduced with increased RH. The effect of RH on actuator thrust was not documented. The authors also examined the effect of RH on current discharge characteristics and noted that the number of positive and negative current peaks generally decreased with increased RH.

Ashpis and Laun [6] performed a systematic investigation to address the apparent nonrepeatability of thrust measurements made with DBD plasma actuators. Their focus was to develop a more reliable method for measuring DBD actuator thrust. In the course of their investigation, they performed measurements at two fixed relative humidity values: a "low" value of $\mathrm{RH} = 18\%$ and a "humid" case of $\mathrm{RH} = 50\%$. They show that increasing relative humidity reduces measured thrust. However, with only two RH values, the functional form of the variation was obviously not determined.

In this study, the effect of RH on the reactive thrust produced by a DBD plasma actuator is systematically investigated. The performance metric of reactive thrust is directly proportional to the actuator-induced body force $\boldsymbol{F}_B = \rho_C \boldsymbol{E}$ and was measured directly by a procedure similar to that used in the plasma actuator optimization study of Thomas et al. [7]. Although the reactive thrust is only proportional to body force, this is sufficient for the purposes of this study because it is the characterization of the change in $\boldsymbol{F}_B$ with RH that is of interest here. Furthermore, results are presented for a wide range of relative humidity, $20\% \le \mathrm{RH} \le 90\%$, and for peak-to-peak applied voltages up to 50 kV. Details regarding the experimental facility are presented in the following section.

II. Experimental Apparatus

As shown in the schematic of Fig. 1, the experimental facility consists of a closed, rectangular test chamber of dimensions 2 m in length and 0.61 m square in cross section (an enclosed volume of 0.74 m^3). This size was sufficient to prevent the actuator from inducing large-scale recirculating flow inside the chamber. To control the RH level, a Hamilton Beach True Air Ultrasonic Humidifier was installed inside the closed chamber. The humidifier produced droplets with a median diameter of approximately 2 μm. The chamber was instrumented with two Honeywell type HIH-4031 RH sensors located on either side of the plasma actuator. These were used for real-time monitoring of the RH inside the chamber. The estimated relative uncertainty of the RH measurement was $\pm 3.8\%$ at 95% confidence. A Vishay NTC thermistor was used to correct the RH for temperature. The reactive thrust from the DBD plasma actuator was measured directly using the same method described in the actuator optimization study by Thomas et al. [7]. The instantaneous thrust produced by the DBD actuator was read directly from the display of an Acculab ALC force balance, which has a resolution of 0.098 mN (0.01 g), whereas RH and temperature readings were made using a Vernier LabQuest data-acquisition system. The relative uncertainty in the thrust measurement was $\pm 4.0\%$ at 95% confidence. To examine lower-than-ambient humidity levels, an Sunpentown (SPT) SD-40E dehumidifier was added to the experimental arrangement shown in Fig. 1. This allowed the RH to be systematically varied over the nominal range of $20\% \le \mathrm{RH} \le 90\%$.

The plasma actuator electrodes were constructed from Copper foil tape of 0.04 mm thickness mounted directly on a 0.318-cm-thick quartz plate dielectric surface. There was zero overlap between the exposed and covered electrodes. The length of the exposed and

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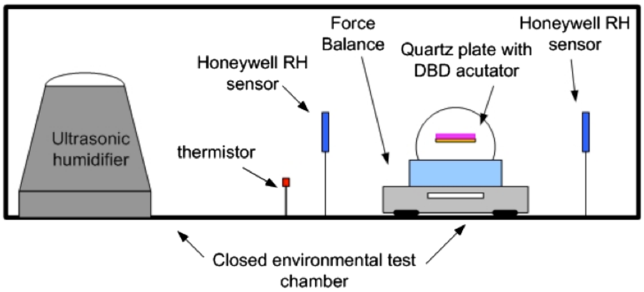

Fig. 1 Schematic of the experimental apparatus.

covered electrodes was 2.54 and 5.08 cm, respectively. The spanwise length of both electrodes was 20.32 cm. The top edge of the exposed electrode and the entire covered electrode were overlayed with two layers of 0.762-mm-thick high-voltage tape (3M Scotch 130C) to avoid the formation of plasma at the edge and rear, respectively. The circuit used to operate the DBD actuator is identical to that presented in figure 6 of Kozlov and Thomas [8]. The plasma actuator was operated with a sinusoidal ac voltage with peak-to-peak amplitude varying from 35 to 50 kV and ac frequency of 2 kHz.

The plasma actuator was oriented such that the resulting plasma-induced flow was directed upward (away from the force balance), and so the reactive thrust acting downward was measured directly by the balance. A block of lightweight insulating foam material supported the actuator. This is also shown schematically in Fig. 1. The leads that power the actuator used thin wires that were not under tension, and so they had no influence on the thrust measurements. The force balance was enclosed in a Faraday cage to minimize electromagnetic noise influencing the force measurements. This procedure was verified by positioning the balance with a fixed, known weight in the vicinity of an operating plasma actuator. The presence of plasma had no influence on the weight measurement.

III. Experimental Results

Within experimental uncertainty, it was found that the reactive thrust produced by the DBD actuator was essentially constant for RH < 40%. In the subsequent discussion, we will denote these (constant) actuator thrust values measured for RH < 40% as T_{DRY}. For the range of applied voltages used in this investigation ($35 \le V_{\mathrm{PP}} \le 50$ kV), it was observed that $T_{\mathrm{DRY}} \propto V^{2.3}$, a result fully consistent with figure 5 of Thomas et al. [7].

For RH > 40% a systematic reduction in actuator thrust occurs and is found to be well represented by a power law of form

$$\left(\frac{T_{\mathrm{DRY}} - T}{T_{\mathrm{DRY}}}\right) = \alpha \left(\frac{P_V}{P_{\mathrm{SAT}}}\right)^{\beta} \tag{1}$$

where α and β are constant for a given applied voltage. An example of this power-law variation for the humidity-induced reduction of reactive thrust is shown in Fig. 2 for the case of $V_{\mathrm{PP}} = 35$ kV. The linear variation shown on this log–log plot clearly indicates that the actuator thrust reduction with relative humidity follows a power law with exponent $\beta = 4.1$.

Figure 3 presents the measured reduction in reactive thrust with RH for the 40 kV case. Again, a log–log scale is used, which clearly indicates a power-law variation of the thrust reduction with RH. Note, however, that for RH > 70% the power-law exponent is reduced. The reduction in power-law exponent commencing near RH = 70% was also observed for the 45 and 50 kV cases as well. A comparison of Figs. 2 and 3 shows that the exponent characterizing the initial power-law variation has changed. In fact, our measurements clearly indicate that the power-law exponents are a function of the applied actuator voltage, although the function form [Eq. (1)] is not. This becomes readily apparent from Fig. 4, which presents the thrust reduction measurements for the 45 kV case. Note that the initial reduction in actuator thrust follows a power law with $\beta_1 = 8.9$. For RH > 70%, the power-law exponent is reduced to $\beta_2 = 6.3$, and it is interesting to note that the ratio of the of the power-law exponents in the two regimes shown in Figs. 3 and 4 (as well as for the 50 kV case) is a constant, $\beta_1/\beta_2 \approx 1.4$. The functional variation of the power-law exponents β_1 and β_2 with applied voltage is shown in the inset to Fig. 4.

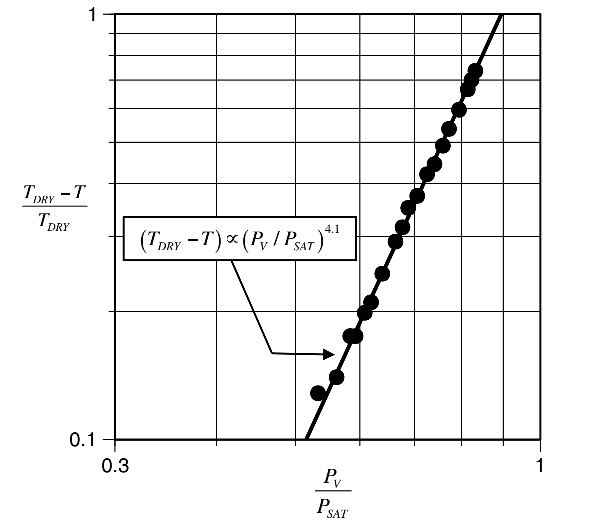

Fig. 2 Measured power-law reduction in actuator thrust for the 35 kV case.

One may question whether the reduction in thrust shown in the previous figures may be simply due to a reduction in air density associated with increased RH. It is easy to show that the density of the air in the chamber, ρ, as a function of RH is given by

$$\rho = \rho_{\mathrm{DRY}} \left(1 - \mathrm{RH} \frac{P_{\mathrm{SAT}}}{P}\right) \tag{2}$$

where ρ_{DRY} is the dry air density, P_{SAT} is the saturation water vapor pressure, and P is the ambient pressure. Equation (2) expresses the well-known fact that air density is reduced with increased relative humidity. Substitution of values consistent with the reported experiments into Eq. (2) shows that, for a relative humidity of 90%, $\rho/\rho_{\mathrm{DRY}} \approx 0.97$, so that one would expect only a 3% reduction in thrust for the highest RH tested (if solely due to reduced density). This is far smaller than the thrust reductions shown in Figs. 2–4, which approach 70%. Furthermore, the reduction in reactive thrust with RH is nonlinear. Equation (2) predicts a linear variation, which is not the case. It is clear from the measurements that the reduction in actuator thrust is not due to a simple density effect.

Figure 5 presents photographs of the DBD plasma actuator discharge for three representative applied voltage cases. Two images

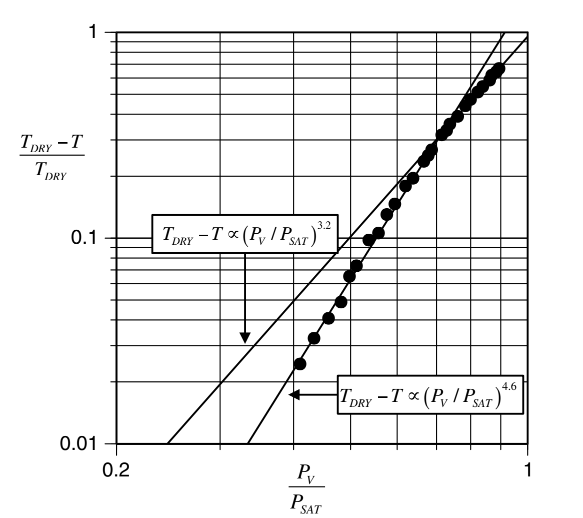

Fig. 3 Measured power-law reduction in actuator thrust for the 40 kV case. Note that the power-law exponent changes for RH > 70%.

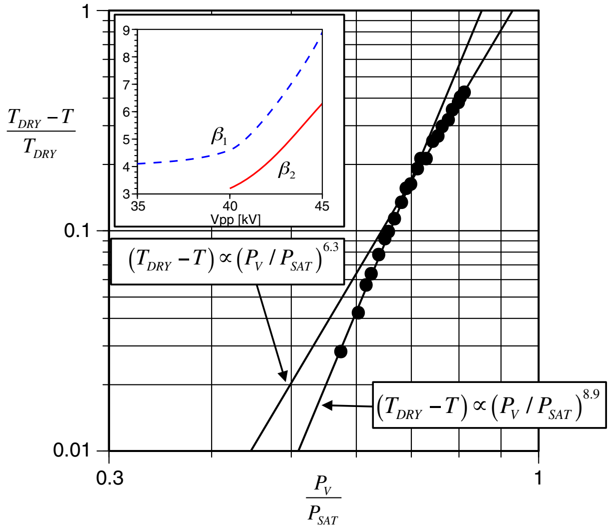

Fig. 4 Measured power-law reduction in actuator thrust for the 45 kV case. Inset: functional variation of β_1 and β_2 with applied voltage for the range of the experiments.

are shown at each applied voltage. The first shows the discharge at ambient relative humidity (RH = 40%) where negligible thrust reduction is observed and the second at a comparatively high relative humidity (RH = 75%). It is apparent that the character of the discharge is markedly changed with increased relative humidity. In particular, Fig. 5 shows a glow discharge that is typical of DBD plasma actuators for each of the RH = 40% cases. In contrast, at RH = 75%, the discharge is infused with multiple discrete filamentary streamers, with the effect most apparent in the two highest applied voltage cases. Photographic evidence shows that the reduction in thrust at increased RH appears associated with the transition from glow discharge to filamentary discharge. At lower actuator voltages, this transition is gradual but it is more sudden at the highest voltages like the 50 kV case. Koo et al. [9] investigated the effect of moisture content on the spatial uniformity of a 13.56 MHz RF-powered dielectric barrier discharge using helium gas. Their study showed that, as the moisture content increased, the character of the discharge changed from uniform glow to streak discharge which is consistent with the results shown in Fig. 5. Figure 6 compares images of the actuator discharge for the experiment with $V_{PP} = 40$ kV (corresponding to the thrust measurements shown in Fig. 3). At below-ambient RH = 15%, a uniform glow discharge is observed, but at RH = 85%, the plasma is dominated by discrete streamers.

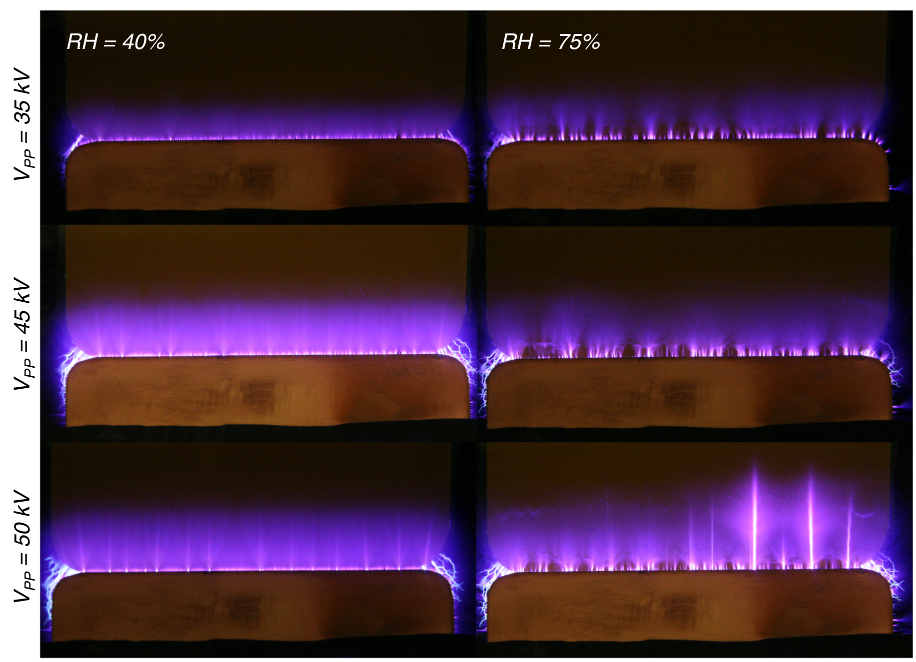

Fig. 5 Photographs of the DBD discharge at ambient and high RH.

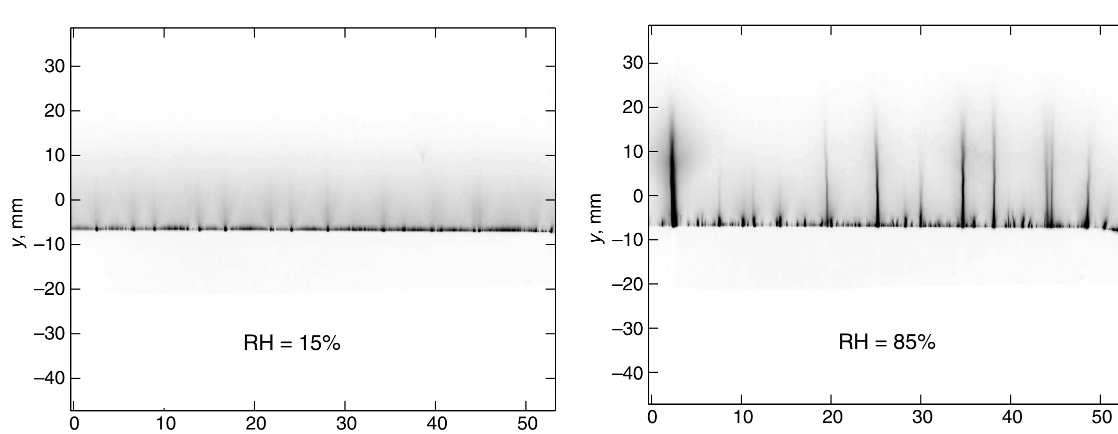

Fig. 6 Photographs comparing the DBD discharge for below-ambient and high RH; $V_{PP} = 40$ kV.

Measurements show that the integrated light emission at high humidity is an order-of-magnitude larger than at low humidity.

It was shown in [7] that, at the highest applied voltages used in DBD plasma actuators, discrete filamentary structures (streamers) developed in the plasma that resemble those shown in Figs. 5 and 6 (see figure 8 of [7] for a comparison). It was shown that, once discrete streamer formation occurred, further increases in applied voltage did not result in a significant increase in the reactive thrust (body force) but dissipated power increased sharply. Because the onset of streamer formation is associated with maximum thrust and an increase in dissipated power, this was referred to as the actuator saturation condition. A focus of [7] was to achieve higher DBD actuator authority by delaying actuator saturation to higher applied voltages. This was achieved by using comparatively thick dielectric barrier materials with low dielectric constant. Together, these functioned to lower the effective capacitance of the actuator, which had the effect of lowering the surface charge density at fixed applied voltage.

Figures 5 and 6 indicate that the effect of increasing RH at fixed applied voltage is to promote discrete streamer formation, thereby lowering the reactive thrust (body force). It is conjectured that this effect is associated with a humidity-induced modification of the charge distribution on the dielectric surface, giving rise to spatial inhomogeneity that reduces the number of microdischarges and promotes discrete streamer formation at preferred locations. This is in contrast to the homogeneous distribution of numerous microdischarges over the dielectric surface that characterizes the glow discharge regime [10]. In addition, it should be acknowledged that plasma chemistry could also play a role in the body force reduction. For example, Kim et al. [11] presented experimental results that indicated the importance of oxygen and oxygen negative ions in the body force produced by DBD plasma actuators. In humid air, the plasma chemistry can be modified to reduce the body force through the creation of active species such as OH and H_2O_2.

IV. Conclusions

Based upon the results of this investigation, it is found that the reduction in reactive thrust produced by the actuator is negligible for RH < 40%. For higher levels of relative humidity, a very significant reduction (approaching 70% in this study) in the actuator-induced thrust is observed. More importantly, the functional variation of thrust reduction with relative humidity is well approximated by a power law in the form of Eq. (1). The power-law exponent is observed to increase with applied voltage. In addition, for the applied voltage cases greater than $V_{PP} = 35$ kV, the power-law exponent is reduced for RH > 70%. Denoting the power-law exponent for 40% ≤ RH ≤ 70% as β_1 and that for RH > 70% as β_2, it was found that, in each case, $\beta_1/\beta_2 \approx 1.41$. Based upon photographs of the discharge at each applied voltage, and for both low and high relative humidity conditions, it is conjectured that the change in power-law exponent for RH > 70% is associated with a reduction in number of microdischarges and the transition to the formation of discrete streamers.

Knowledge of the functional variation of dielectric barrier discharge (DBD) actuator thrust reduction with relative humidity (RH) provides important information required for the design of actuator humidity compensation circuits. Using such a unit, the detrimental effect of RH can be fully compensated by increasing the actuator operating voltage by the appropriate amount. Of course, this presumes that the dielectric material and thickness as well as ac frequency is suitable for operating at the required elevated voltages without transitioning to the filamentary discharge regime observed in [7]. One can envision in-flight measurement of RH with similar small, solid-state RH sensors as used in these experiments. With RH determined, and the functional dependence on actuator thrust known a priori, the DBD-actuator operating voltages could be automatically increased by a previously prescribed amount to fully compensate for any RH induced performance loss.

Future work should focus on the mechanism of filament formation at high RH, which may provide insight into the design of dielectric materials/surfaces more suitable for high-RH environments.

Finally, it should be noted that the generality of power-law relation (1) remains an open question. It remains to be determined whether the functional reduction in reactive thrust with RH as documented in this Note can be generalized to other DBD actuator geometric configurations.

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