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Technical Notes

Plasma Catalysis for Enhanced-Thrust Single Dielectric Barrier Discharge Plasma Actuators

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I. Introduction

SINGLE dielectric barrier discharge (SDBD) plasma actuators have been used to manipulate airflows on a variety of lifting and nonlifting bodies (see, for example, the excellent review article by Corke et al. [1]). These actuators, which consist of a pair of offset electrodes separated by a dielectric material, generate a force on the neutral background gas that results in a paraelectric gas flow. Applications include, for example, active delay of separation near the leading edge of airfoils [2,3], delay of airfoil dynamic stall [4,5], reduction of bluff-body drag by delay of separation [6,7], control of separation on turbomachinery blades [8,9], flow control on wind turbine blades [10], and other similar applications.

While plasma actuators have been used with some success, as detailed in the literature cited above, their utility is limited by the small force that is generated by the actuators. The thrust generated by state-of-the-art actuators is limited to about 0.10 to 0.20 N per meter of actuator, inducing a velocity that peaks at about 3.0 to about 6.0 m/s [1]. Although their attributes (particularly the ability to be flush-mounted with almost no parasitic drag, very simple implementation, and no moving parts) make them very attractive for active flow control, it is generally recognized that a significant increase in control authority is needed in order for plasma actuators to be effective for most practical applications.

One approach to increasing actuator thrust may be to apply certain heterogeneous catalysts on the surface of the dielectric exposed to the plasma. In this Note, we present the results of recent experiments using titania (TiO_2) as a plasma catalyst in which the actuator thrust was seen to increase by as much as 120% relative to the catalyst-free actuator. We discuss possible mechanisms responsible for the enhanced thrust and suggest further experiments which will improve our understanding of the phenomenon.

II. Experimental Procedure

An SDBD plasma actuator was constructed and used to investigate the force generated with and without a titania catalyst. Figure 1 illustrates the experimental setup. A single pair of electrodes was separated by a square alumina ceramic plate having a length of 15 cm and a thickness of 0.635 mm. The exposed electrode consisted of a 25.4-mm-wide by 127-mm-long copper foil tape with 0.089 mm (3.5 mil) thickness. The covered electrode was 50.8-mm-wide by 127-mm-long copper foil tape with the same thickness as the exposed electrode. The lower edge of the exposed electrode, as shown in Fig. 1, was approximately 25 mm from the lower edge of the ceramic plate. Each edge of the two electrodes, with the exception of the long edge of the exposed electrode adjacent to the plasma zone, was covered with 0.065-mm-thick (2.5 mil) Kapton® tape. Two layers of 3M Scotch 130C dielectric tape were used to cover the back side of the alumina ceramic. The electrodes were connected to a power supply which provided up to 16 kV (rms) of electrical potential across the electrodes. The power supply consisted of a Titan MAC-02 mainframe amplifier with a Titan MOS-01 oscillator coupled to a pair of Crown 25X step-up transformers. A 5 kHz sinusoidal waveform was applied. The actuator was placed in a Plexiglas® stand resting on an OHAUS A812 precision scale capable of measuring forces up to 812 g with a precision of 0.01 g. The actuator and scale were housed in a Plexiglas box to isolate the apparatus from extraneous airflow. A duct with a 3 in. ac cooling fan was connected to the box to siphon off ozone and N_xO_y gases produced by the plasma. A manganese oxide honeycomb catalyst was placed over the duct entrance to partially remove the ozone generated by the plasma and to introduce an additional pressure loss to reduce the flow disturbance in the closed container.

After placing the actuator on the scale, closing the container and turning on the fan in the duct, the pressure in the container was allowed several minutes to settle to a steady state (approximately 5 min). The weight of the actuator and holding apparatus was then read from the scale's digital output screen and manually recorded with the voltage off. The weight was then measured and recorded for rms voltages of 4.0, 4.5, 5.0, 5.5, 6.0, and 6.5 kV. At higher voltages, the plasma saturated and no additional force was generated: a phenomenon described by Thomas et al. [11]. For each measurement, the voltage was set manually using the MOS-01 oscillator and a high-voltage probe connected to a Tektronix 3016B digital oscilloscope. Very little time lapsed between measurements, so that the total time required to measure the force at all six voltage settings was approximately 5 min. Following the measurement at 6.5 kV, the voltage was returned to zero and the static weight was again measured and recorded. The measurements were then repeated for a total of four trials in succession in order to estimate the variability in the results. Only a few minutes separated each successive trial.

Following the fourth trial, the actuator was removed from the scale and the dielectric surface above the covered electrode (extending the entire 15 cm width of the actuator and roughly 25 mm in the downstream direction; see Fig. 1) was coated with a thin layer of liquid consisting of 5000–8000 ppm nanoparticle-sized TiO_2 (anatase form) and 25–50 ppm Zn in water. The mixture used was a commercial product sold as OxiTitan® (Ecoactive Surfaces, Inc.). For the remainder of this Note, we will refer to the OxiTitan mixture as *the catalyst*. The liquid mixture was sprayed on with a single pass of an air brush powered by compressed air and set to a low volumetric flow rate. Following application of the mixture, the dielectric was dried for approximately 1 h by placing the ceramic roughly 7–10 cm in front of a 500 W halogen bulb. After drying (and after letting the pressure in the chamber settle for approximately 5 min), the actuator and holding apparatus were returned to the scale and the force was again measured for rms voltages of 4.0, 4.5, 5.0, 5.5, 6.0, and 6.5 kV. As before, the measurements were repeated four times in succession in order to estimate variability.

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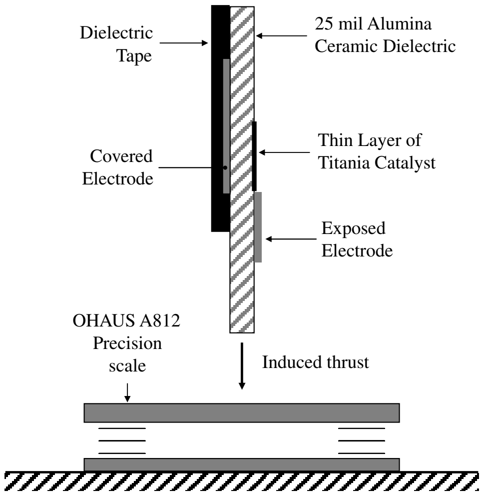

Fig. 1 Illustration of the experimental apparatus.

The procedure described above was repeated four times (for a total of five actuators), each time with a new actuator (all five were constructed in a consistent manner). For the fifth actuator, however, a false catalyst (tap water) was used in place of the titanium dioxide/zinc mixture. This was done to rule out the possibility that the measurement procedure introduced a variation caused by something other than the catalyst.

III. Results

The results of the actuator force measurements with and without the catalyst are presented in Fig. 2. In Fig. 2a, which shows a sample result for a single actuator, the force is plotted as a function of applied voltage with (solid line) and without (dashed line) the catalyst. The actuator force is recorded as the difference between the weight measured by the precision scale with the plasma activated and the static weight measured with the plasma off. Each data point in the two curves shown in Fig. 2a represents the average actuator force measured over four successive measurements, and the error bars represent the high and low measurements at each voltage. The error bars are therefore a measure of the variability in the results, not the statistical error (which would be meaningless with such a limited data set). The variability is likely due to a combination of imprecision in the voltage and frequency settings, the force measurements, and varying environmental factors such as the temperature, pressure and secondary flows in the chamber.

Although it seems natural to assume that the catalyst is susceptible to ablation or some other physical or chemical erosion process, there was no monotonic trend in the thrust enhancement from the first trial to the fourth trial for any of the four actuators that used the titania catalyst. However, we recognize that this experiment was not sufficient to characterize the behavior of the catalyst over time.

Figure 2b shows the results of the actuator force measurements with the false catalyst (water). As mentioned above, the purpose for making this measurement was to isolate the effect of the OxiTitan. It was not a blind test (the experimenter knew that it was a false catalyst), but the results are nevertheless a good indication that the observed thrust enhancement was caused by the addition of the titania catalyst and not by any other physical effect (such as heating of the dielectric).

Figure 2c shows the average, high, and low of the actuator force measurements, represented as the percent increase over the actuator force with no catalyst. While Fig. 2a shows the magnitude of the force with and without the catalyst for a single actuator experiment, Fig. 2c presents the percent change in actuator force for all four independent actuator experiments. To further clarify by example, each data point plotted in the average percent change (the thick solid line in Fig. 2c), represents the average of 16 independent measurements (four separate but similarly constructed actuators, and four successive measurements for each). As is evident in Fig. 2, the variability between separate actuators is much greater than the variability between successive measurements for a single actuator (represented by the error bars in Fig. 2a). The principal causes of this actuator-to-actuator variability are likely differences in the construction of the actuators (e.g., small changes in the electrode overlap and the electrode lengths), the amount of titania applied, the distribution of titania, the environmental conditions during drying (the distance from the drying lamp, for example), and possibly the surface energy of the dielectric before application of the catalyst resulting from previous plasma activation. It is worth noting, however, that we

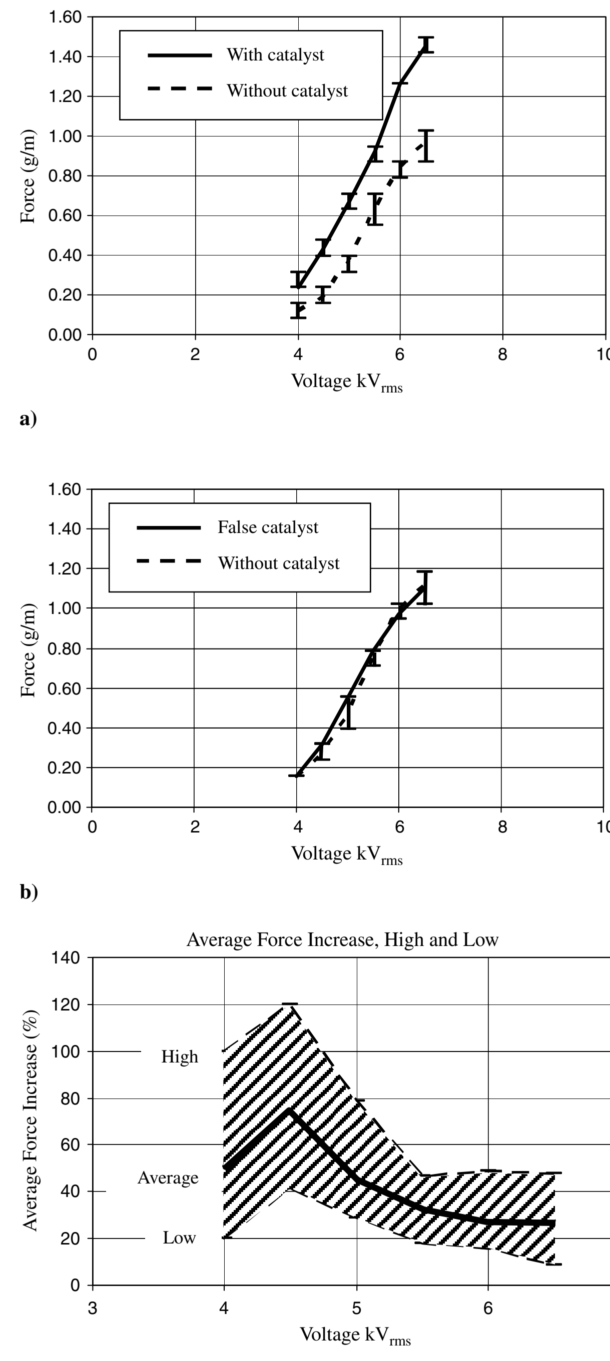

Fig. 2 Plots of a) sample measurement of force per unit meter of actuator generated by an SDBD actuator and measured with and without a titania catalyst; b) measurement of the effect of a false catalyst, confirming that the thrust enhancement with the catalyst is not introduced by the measurement procedure; and c) composite % increase of catalyst-enhanced thrust measured in the proof-of-principle experiment (solid line represents the average force increase, ad the two dashed lines are maximum and minimum force increases).

observed significant variation in the thrust generated by the five actuators before application of the catalyst. For example, taking the high and low force generated at 5 kV without the catalyst and assuming that the average is at the midpoint between those two measurements yields a variation of $\pm 33\%$. The equivalent variation at that voltage for the case with the catalyst (from Fig. 2c) is $\pm 40\%$, suggesting that a significant portion of the variation is likely to be due to physical differences between the actuators and the individual measurement conditions and having nothing to do with the application or distribution of the catalyst.

The results summarized in Fig. 2 clearly indicate that a consistent, repeatable, and significant increase in actuator force is obtained through use of the titanium dioxide/zinc catalyst. Note that the experiment was not designed to show optimum actuator performance; higher forces are expected to result from optimizing the physical parameters of the actuator design using lessons learned by other researchers (as summarized by Corke et al. [1]), including selecting a lower dielectric-constant dielectric material, increasing the dielectric thickness, using a sawtooth voltage waveform with higher rms voltage, optimizing the frequency, and modifying other geometric and physical parameters.

It should be noted that although we made every attempt to be consistent in our experiment from one actuator to the next, no attempt was made to quantify the amount of titania applied to the dielectric or to measure the physical or chemical characteristics of the catalyst either before igniting the plasma or after the experiment was performed. Such measurements would be helpful in understanding the variability in the results. More robust methods for fixing the catalyst to the surface of the dielectric, such as the sol-gel method [12], will also be considered in the future.

IV. Discussion

The experiment presented herein was motivated in part by previous research concerning the application of plasma catalysis to the abatement of certain hazardous air pollutants [13–15]. When applied to the oxidation of volatile organic compounds (VOCs), for example, heterogeneous catalysts have been seen to dramatically increase the oxidation efficiency of nonthermal atmospheric plasmas. Van Durme et al. [13] found that when titania was added to a dielectric barrier discharge plasma, it tripled the rate at which toluene was oxidized in air. Chevadey et al. [15] found a similar synergistic effect and suggested that titania catalysts cause an increase in the local concentrations of certain charged species in the plasma (primarily oxygen radicals including the superoxide radical anion $O_2^{\bullet -}$) creating increased local nonthermodynamic equilibria and a denser mix of reactive species. It was Chevadey et al.'s suggested mechanism that led us to consider applying plasma catalysis to SDBD plasma actuators. In those regions where there is an increase in the net charge density resulting from higher local concentration of charged species, we hypothesize that the electrostatic field generated by the plasma actuator will result in a greater number of collisions between ions and the neutral background gas, yielding the observed increase in actuator thrust.

The hypothesis that the titania has a catalytic effect on the plasma chemistry, resulting in a greater density of oxygen ions, may be supported by observations and measurements reported first by Enloe et al. [16] (later confirmed by others and summarized by Corke et al. [1]) that describe increasing actuator force in proportion to the oxygen partial pressure. These studies suggest that the negative ions that are formed when electrons attach to oxygen molecules play a significant role in generating the actuator thrust. Since others have measured increased production of oxygen ions through catalytic chemistry in the plasma [15], it seems that our catalysis hypothesis is consistent with the results of these oxygen concentration experiments. Nevertheless, other possible explanations must be considered before the phenomenon can be fully understood. Other suggested explanations include local spikes in the electric field near the titania particles, dusty plasma effects, the effect of other unknown chemicals in the OxiTitan, and changes in the charge distribution on the dielectric surface. The latter hypothesis is supported by studies that have shown that certain semiconducting metal oxide coatings on circuit boards can have sufficient conductivity to beneficially redistribute charge on a surface while retaining enough resistivity to prevent short circuits (e.g., Frederickson et al. [17]). Other plasma actuator studies have established the importance of surface charge distribution on actuator performance and means by which the charge distribution can be controlled in order to increase actuator thrust [18,19]. Since titania is also a semiconductor, it seems highly likely that its presence on the surface of the dielectric will affect the charge distribution. This phenomenon must therefore be considered a plausible explanation of our observations and be given due consideration in further research.

Given the significant increase in actuator thrust seen in this experiment with almost no process optimization, we feel that further research is warranted. To better understand the observed phenomenon, we intend to examine the effect of the catalyst on the production of certain charged species by measuring their concentrations in the plasma using optical emission spectroscopy. We also intend to look for such species on the surface of the dielectric where the catalyst is deposited to reveal intermediate byproducts and to seek further evidence to support (or revise) the charged-species hypothesis. Additional experiments to examine the effect of the catalyst on electron density and electric field strength are planned to help elicit an improved understanding of the enhanced force. Examination of the resistivity of the titania coating would be helpful in examining the role of charge distribution on the dielectric surface.

Other potential catalysts will be considered in addition to titania. Transition metals (such as platinum, palladium, gold, and others) along with various metal oxides (such as aluminum oxide, zinc oxide, magnesium oxide, and others) have proven to be effective in plasma catalysis for a VOC oxidation [13,20] and may prove effective for the present application.

V. Conclusions

Results of the experiments described herein indicate that the force exerted on the background gas by a single dielectric barrier discharge plasma actuator is increased up to 120% by the addition of a titania catalyst within the plasma volume. We hypothesize that this enhancement is due to increases in the rate at which certain charged species are generated in the plasma volume. Additional experiments are suggested to better understand the phenomenon so that it can be put to practical use in active flow control applications.

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References

[1] Corke, T. C., Enloe, C. L., and Wilkinson, S. P., "Dielectric Barrier Discharge Plasma Actuators for Flow Control," *Annual Review of Fluid Mechanics*, Vol. 42, 2010, pp. 505–529. doi:10.1146/annurev-fluid-121108-145550

[2] Post, M. L., and Corke, T. C., "Separation Control on a High Angle of Attack Airfoil Using Plasma Actuators," *AIAA Journal*, Vol. 42, No. 11, 2004, pp. 2177–2184. doi:10.2514/1.2929

[3] Benard, N., Braud, P., and Jolibois, J., "Airflow Reattachment Along a NACA 0015 Airfoil by Surface SDBD Actuator-Time Resolved PIV Investigation," AIAA Paper 2008-4202, 2008.

[4] Post, M. L., and Corke, T. C., "Separation Control Using Plasma Actuators—Dynamic Stall Vortex Control on an Oscillating Airfoil," *AIAA Journal*, Vol. 44, No. 12, 2006, pp. 3125–3135. doi:10.2514/1.22716

[5] Roth, J. R., "Optimization of the Aerodynamic Plasma Actuator as an EHD Electrical Device," 44th AIAA Aerospace Sciences Meeting, AIAA Paper 2006-1203, Jan. 2006.

[6] Do, H., Kim, W., Mungal, M. O., and Cappelli, M. A., "Bluff Body Flow Separation Control Using Surface Dielectric Barrier Discharges,"

AIAA Paper 2007-939, 2007.

[7] Thomas, F. O., Kozlov, A., and Corke, T. C., "Plasma Actuators for Cylinder Flow Control and Noise Reduction," *AIAA Journal*, Vol. 46, No. 8, 2008, pp. 1921–1931.
doi:10.2514/1.27821

[8] Huang, J., Corke, T. C., and Thomas, F. O., "Plasma Actuators for Separation Control of Low-Pressure Turbine Blades," *AIAA Journal*, Vol. 44, No. 1, 2006, pp. 51–57.
doi:10.2514/1.2903

[9] Huang, J., Corke, T. C., and Thomas, F. O., "Unsteady Plasma Actuators for Separation Control of Low-Pressure Turbine Blades," *AIAA Journal*, Vol. 44, No. 7, 2006, pp. 1477–1487.
doi:10.2514/1.19243

[10] Nelson, R. C., Corke, T. C., Othman, H., Patel, M. P., Vasudevan, S., and Ng, T., "A Smart Wind Turbine Blade Using Distributed Plasma Actuators for Improved Performance," AIAA Paper 2008-1312, 2008.

[11] Thomas, F. O., Corke, T. C., Iqbul, M., Kozlov, A., and Schatzman, D., "Optimization of Dielectric Barrier Discharge Plasma Actuators for Active Aerodynamic Flow Control," *AIAA Journal*, Vol. 47, No. 9, 2009, pp. 2169–2178.
doi:10.2514/1.41588

[12] Anderson, M. A., Gieselman, M. J., and Xu, Q., "Titania and Alumina Ceramic Membranes," *Journal of Membrane Science*, Vol. 39, 1988, pp. 243–258.
doi:10.1016/S0376-7388(00)80932-1

[13] Van Durme, J., Dewulf, J., Leys, C., and Langenhove, H. V., "Combining Non-Thermal Plasma with Heterogeneous Catalysis in Waste Gas Treatment: A Review," *Applied Catalysis B, Environmental*, Vol. 78, 2008, pp. 324–333.
doi:10.1016/j.apcatb.2007.09.035

[14] Ayrault, C., Barrault, J., Tatibouet, J-M., Pasquiers, S., and Tardiveau, P., "VOC Removal by a Plasma-Catalytic Process," *57th Gaseous Electronics Conference*, American Physical Society, College Park, MD, 2004.

[15] Chevadey, S., Kiatubolpaiboon, W., Rangsunvigit, P., and Sreethawong, T., "A Combined Multistage Corona Discharge and Catalytic System for Gaseous Benzene Removal," *Journal of Molecular Catalysis A: Chemical*, Vol. 263, No. 1, 2007, pp. 128–136.
doi:10.1016/j.molcata.2006.08.061

[16] Enloe, C., McLaughlin, T., Font, G., and Baughn, J., "Parameterization of Temporal Structure in the Single Dielectric-Barrier Aerodynamic Plasma Actuator," *AIAA Journal*, Vol. 44, 2006, pp. 1127–1236.
doi:10.2514/1.16297

[17] Frederickson, A. R., Nanevicz, J. E., Thayer, J. S., Enloe, C. L., Mullen, E. G., and Parkinson, D. B., "Leaky Insulating Paint for Preventing Discharge Anomalies on Circuit Boards," *IEEE Transactions on Nuclear Science*, Vol. 36, No. 6, Pt. 1, 1989, pp. 2405–2410.

[18] Enloe, C., Font, G., McLaughlin, T., and Orlov, D., "Surface Potential and Longitudinal Electric Field Measurements in the Aerodynamic Plasma Actuator," *AIAA Journal*, Vol. 46, 2008, pp. 2730–2740.
doi:10.2514/1.33973

[19] Opaits, D., Shneider, M., Likhanskii, A., Zaidi, S., Macheret, S., and Miles, R., "Improving Thrust by Suppressing Charge Build- Up in Pulsed DBD Plasma Actuators," 47th AIAA Aerospace Sciences Meeting, AIAA Paper 2009-487, Orlando FL, Jan. 2009.

[20] Chen, H. L., Lee, H. M., Chen, S. H., Chang, M. B., Yu, S. J., and Li, S. N., "Removal of Volatile Organic Compounds by Single-Stage and Two-Stage Plasma Catalysis Systems: A Review of the Performance Enhancement Mechanisms, Current Status, and Suitable Applications," *Environmental Science and Technology*, Vol. 43, 2009, pp. 2216–2227.
doi:10.1021/es802679b

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