Dielectric Barrier Discharge (DBD) Plasma Actuators for Flow Control in Turbine Engines: Simulation of Flight Conditions in the Laboratory by Density Matching

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Abstract: We address requirements for laboratory testing of AC Dielectric Barrier Discharge (AC-DBD) plasma actuators for active flow control in aviation gas turbine engines. The actuator performance depends on the gas discharge properties, which, in turn, depend on the pressure and temperature. It is technically challenging to simultaneously set test-chamber pressure and temperature to the flight conditions. We propose that the AC-DBD actuator performance depends mainly on the gas density, when considering ambient conditions effects. This enables greatly simplified testing at room temperature with only chamber pressure needing to be set to match the density at flight conditions. For turbine engines, we first constructed generic models of four engine thrust-classes; 300-, 150-, 50-passenger, and military fighter, and then calculated the densities along the engine at sea-level takeoff and altitude cruise conditions. The range of chamber pressures that covers all potential applications was found to be from 3 to 1256 kPa (0.03 to 12.4 atm), depending on engine-class, flight altitude, and actuator placement in the engine. The engine models are non-proprietary and can be used as reference data for evaluation requirements of other actuator types and for other purposes. We also provided examples for air vehicles applications up to 19,812 m (65,000 ft).

Keywords: DBD plasma, flow control, turbine-engine

PACS® (2010). 52.77.-j

Introduction

There has been a long time strong interest in active flow control techniques focusing on manipulation of external flows and improving aerodynamic performance of air vehicles [1, 2]. Opportunities for internal flow manipulation using active flow control exist also in gas turbine engines, as pointed out by Lord et al. [3]. The most common active flow control techniques in aerodynamics are based on injection of steady, unsteady, or oscillatory momentum into the boundary layer via small jets. The small input creates a large global effect that provides the desired flow improvement, e.g. delayed separation, increased stall angle, reduced drag, decreased separation, reduced noise, etc.

Dielectric Barrier Discharge (DBD) plasma actuators create steady or unsteady momentum by purely electronic means, and can serve as the momentum injection source for active flow control, similar to any pneumatically- or mechanically-generated jet [4]. A planar DBD actuator is shown in Figure 1(a). The actuator consists of a pair of thin conducting offset electrodes separated by a dielectric. A DBD actuator can operate in different modes, designated AC-DBD or NS-DBD, depending on the type of applied voltage. In the AC-DBD mode, a high voltage, high frequency, signal (typically 1 to 40 kV RMS, 1 to 20 kHz) is applied to the electrodes. The signal can be sinusoidal or other waveform and can be modulated or pulsed in a duty-cycle. In the NS-DBD mode, repetitive ultra-short pulses at nanosecond time scale range are applied with repetition rates typically in the range of 1–200 kHz. In either mode the high voltage creates localized weakly ionized gas plasma discharge on the surface that generates momentum via the electrohydrodynamic effect, a process of collisions between ions and neutral molecules in the plasma. An image of a typical discharge is shown in Figure 1(b).

In AC-DBD, gas is drawn from the surroundings to form a thin wall-jet that is roughly parallel to the surface and directed away from the exposed electrode edge in the direction of the covered electrode. There is slight heating involved, but its effect is negligible, and the wall-jet is dominant. In the NS-DBD mode, a combination of localized heating and momentum is generated, depending on the characteristics of the applied voltage signal. When the heating is intense, pressure waves are generated, and
the train of repetitive pressure waves serves as the control mechanism.

More detailed information and references on AC-DBD actuators and their application for aerodynamic flow control can be found in several comprehensive review articles including Moreau [5], Corke et al. [6–8], Benard and Moreau [9], Kotsonis [10], and Kriegseis et al [11]. For the NS-DBD actuators, see Roupassov et al. [12]. Combinations of AC-DBD and NS-DBD were reported by Starikovskiy et al. [13]. For completeness we note that there are also arc discharge actuators. These include the localized arc filament actuator [14], spark jet [15, 16], and the cathodic arc-jet [17, 18].

In this work we focus on AC-DBD devices, the other types of actuators are not addressed. It is possible that ideas limited to the AC-DBD presented here may be extended to these actuators in the future.

The advantages of DBD actuators are that they are surface-mounted, fully electronic, low power, and fast-response devices. There are no moving parts, tubes, ducts or surface holes. Flexible operation is possible by electronically controlling the input voltage and waveforms. DBD plasma actuators are particularly attractive for gas turbine engine applications. They can be accommodated in the constrained space and thin airfoils typical to turbomachinery, as they are surface mounted, thin, and do not require internal passages or tuned volumes for resonance. Their construction can be made suitable for the typical propulsion high-temperature environment by choosing high-temperature alloys for the electrodes and temperature-resistant ceramic materials for the dielectric. They can easily be integrated with futuristic engine components to be made of ceramics and composites.

As can be seen in the review articles cited above, the majority of the research in the DBD actuators area has been focused on applications in external flows, particularly for wings and airframes, rather than on propulsion. But there have been limited, but important, efforts directed at turbomachinery applications. There have been several successful experimental demonstrations of active flow control with AC-DBD plasma actuators to eliminate low Reynolds number separation in Low-Pressure Turbine (LPT) flows (Hultgren and Ashpis [19]; List et al. [20]; Huang et al. [21, 22]; Boxx et al. [23]; Burman et al. [24, 25]; Marks et al. [26]; Matsunuma and Segawa [27]; Pescini et al. [28]), and to reduce effects of turbine tip leakage, with flat actuators (Morris et al. [29]; VanNess et al. [30]; Douville et al. [31]; VanNess et al. [32, 33]), or with string actuators (Matsunuma and Segawa [34, 35]). The cited experiments were performed in wind tunnels or in linear cascades at room temperature. The only known experiment in a rotating turbomachinery facility using AC-DBD actuators was reported by Saddoughi et al. [36], where experiments in a rotating compressor rig demonstrated successful delay of compressor stall. Another rotating rig experiment was reported by McGowan et al. [37]. They used pulsed-DC actuators (which are essentially similar to NS-DBD) in a rotating axial fan facility, and successfully showed delay of the fan stall. Numerical simulations of plasma flow control in turbomachinery have been performed by several researchers, for example Vo [38]. However, there are no known experiments at high temperatures typical to propulsion, and neither are there known experiments in actual engines in ground facilities.

The final phase of technology development usually involves flight tests. Only a very small number of flight tests with plasma flow control systems have been performed with air vehicles. They include: a small remotely controlled airship [39, 40], a full-size piloted glider [41], a small UAV [42], and a full size motorized glider [43, 44]. In comparison, there are no known tests of plasma flow controlled turbine engines in flight. It is expected that this serious gap in research will be filled by future flight testing of various plasma flow control concepts in airframes and turbine-engines.

Prior to flight tests it is desirable to perform wind tunnel tests, and in either case it is prudent to first perform basic characterization of the AC-DBD actuator without external flow to measure its control authority, its power consumption, perform optimization, and choose or develop the power supply. Most of these tests to date have been performed at room temperature and pressure, but in order to test in flight conditions the actuator must be placed in a test chamber with controlled temperature and pressure identical to the
conditions in flight. The reason is that the plasma discharge physical and chemical mechanisms are temperature and pressure dependent [45], hence the induced momentum depends on the local pressure and temperature at the location of the actuator. The aerodynamic performance is then characterized by measuring the velocity profile of the wall jet and/or the thrust generated by the actuator. The electrical performance is characterized by measuring the current, voltage, and power. Only a small number of tests in chambers are reported in the literature, and with one known exception, they are all at room temperature. Tests at sub-atmospheric pressures were performed with AC-DBD (Gregory et al. [46]; Abe et al. [47]; Schuele and Corke [48]; Schuele [49: Appendix D]; Takagaki et al. [50]; Benard et al. [51, 52]; Font et al. [53]; Soni and Roy [54]; Friz and Rovey [55]), with NS-DBD (Starikovskiy and Pancheshnyi [56]), and with combinations of AC and NS-DBD (Starikovskiy et al. [13]). The only tests where temperature and pressure were varied simultaneously to simulate atmospheric flight were performed in an environmental test chamber by Benard and Moreau [57] with an AC-DBD actuator, and by Benard et al. [58] with a NS-DBD actuator. Tests at above-atmospheric pressures at room temperature that were mainly motivated by application in internal aerodynamics and gas turbine engines were reported by Valerioti [59] and Valerioti and Corke [60].

Laboratory testing to match turbine engine conditions are particularly challenging because of the high temperatures and high pressure ratios in several engine components. In practice it is an engineering challenge to simultaneously set pressure and high temperature in a test chamber. Performing diagnostic measurements at high temperature is challenging as well. Therefore this paper is motivated by the desire to find a simpler approach to eliminate this technical complication.

We propose to use the density as the similarity parameter for AC-DBD plasma actuators laboratory testing. Because the operation of DBD actuators depends on electrical discharges and on the associated force generation mechanisms, which, in turn, are pressure and temperature dependent, the performance of the actuator will be affected by the pressure and temperature. We propose that the gas density is the significant parameter influencing the performance of the AC-DBD actuator for the range of temperatures and pressures encountered in the turbine engine over its operating envelope. Therefore, the DBD actuator performance in flight conditions can be simulated by matching the density at room temperature in the laboratory to the density in flight. It is a simple idea that has not been proposed before.

The outline of this paper is as follows. After addressing a relatively simple case of an air vehicle flying at altitude, attention is focused on the turbine engine applications. First, the density distribution is calculated along the flow-path of four thrust-class turbine engines. This information is derived from engine models that we developed specially for the purpose of obtaining non-proprietary information, and include cycle, flow path, and sizing. Then we calculate the test-chamber pressure at room temperature needed to match the chamber density to the in-flight density. The required chamber pressures depend on the placement of the actuator in the engine and the flight altitude, and the results are presented for the four engine-classes at sea-level takeoff and altitude cruise conditions. This information is useful as a guideline for testing requirements of DBD plasma actuators at engine flight conditions. The engine information, which is often hard to find in publicly available sources, can serve as reference data and is useful for evaluation of other types of actuators as well as for other purposes.

**Turbine engine data source—engine models**

The engine models used in this study were developed based on information available in the open literature and from empirical estimates. These models were designed using the Numerical Propulsion Simulation System (NPSS) code (Lytle [61]; Jones [62]; NPSS [63]). NPSS is an object-oriented program that allows one to perform thermodynamic cycle analysis using predefined or user-defined air-breathing engine components, by specifying a thermodynamic package that determines fluid properties, and solving conservation of mass, energy, and momentum equations. Given engine input and design conditions provided by the user, NPSS will size the engine components and use scaled turbomachinery maps to output performance parameters such as thrust, component pressure ratios, velocities, temperatures, and pressures at each engine station. Another object-oriented program, Weight Analysis of Turbine Engines (WATE) code (Tong and Naylor [64]), uses predefined or user-defined engine components, along with the NPSS thermodynamic output and a materials database, to perform aeromechanical analysis, to estimate engine and
component weights, and to generate a flow path schematic of the engine.

Generic engine models representing four different thrust-classes were developed: 300-, 150- and 50-passenger (PAX) aircraft engines, and a military jet-fighter engine. These models are a good representation of actual engines, based on comparisons with proprietary engines information performed over the years by NPSS/WATE developers and users. Note that the 150 PAX model is a conceptual design of a generic geared high bypass turbofan. The primary engine parameters of thrust, weight, overall pressure ratio, and bypass ratio are listed in Table 1 and the schematic of each engine class is shown in Figure 2.

Engine conditions were calculated at the inlet and exit flow stations of the various engine components. Data were acquired for two engine operating conditions: sea-level takeoff, and altitude cruise at 10,668 m (35,000 ft). Data for the 50 PAX engine was also calculated for an additional cruise altitude of 19,812 m (65,000 ft), as this type of engine is also used for air vehicles flying at high altitudes. Figures 3 and 4 show an example of static and total (stagnation) temperature and pressure for the 300 PAX engine. The density for the four classes of engines is displayed in Figures 5–8. The full report [65] includes additional information for the four engine classes, such as static and stagnation pressure, temperature and density, unit Reynolds number, Mach number and velocity. Ideal gas conditions were assumed. For all data shown, the flight Mach numbers are $M = 0.8$ at cruise, and $M = 0$ at takeoff. The 50 PAX engine data in [65] also includes unit Reynolds number for cruise Mach numbers of $M = 0.5$, 0.6, and 0.8 at altitude of 19,812 m (65,000 ft). It is hard to find non-proprietary actual engine data for studies such as this. The engine data presented here and in [65] are unrestricted and can be used for other purposes as well.

### Test conditions for DBD plasma actuators

#### Assumptions

Several assumptions are used to develop the test conditions in laboratory experiments in quiescent environment (no flow) in a test-chamber:

1. The effects of temperature and pressure on plasma kinetics and chemistry are ignored. This assumption is reasonable for the range of temperatures in the turbine engines, and is further discussed below.

2. The effect of temperature on the electrical properties of the actuator, particularly on the capacitance of the dielectric, is negligible. The capacitance variation was calculated in [57] and was shown to be small. However in [58] the reduced permittivity of the dielectric at low temperature (-50°C) affected the results (note that the tests were for NS-DBD).

3. Actuator heat generation is negligible. This assumption is based on experimental observations for the range of power and voltages applied to AC-DBD plasma actuators.

4. Gas thermodynamic properties are constant (except in the engine model data calculations).

5. Gas composition effects are ignored. There is a small effect of the composition of the atmosphere variation with altitude mainly due to variation of the oxygen/nitrogen ratio [53]. Effects due to the presence of combustion products in the areas of the engine downstream of the combustors, and effects of humidity are assumed to be insignificant.

6. Gas viscosity is assumed not to affect the actuator performance. In principle, viscosity dependence on temperature can affect the development of the wall-jet generated by the actuator.

### Table 1: Parameters of four engine models.

<table>
<thead>
<tr>
<th>Engine</th>
<th>Thrust</th>
<th>Weight</th>
<th>OPR</th>
<th>BPR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>At sea-level static</td>
<td>Bare engine</td>
<td>At sea-level</td>
<td>At 10,668 m (35k ft)</td>
</tr>
<tr>
<td></td>
<td>kg (lb)</td>
<td>kg (lb)</td>
<td>Overall Pressure Ratio</td>
<td>Bypass Ratio</td>
</tr>
<tr>
<td>300PAX</td>
<td>39,327 (86,700)</td>
<td>8,346 (18,400)</td>
<td>37.8</td>
<td>45.7</td>
</tr>
<tr>
<td>150PAX</td>
<td>10,614 (23,400)</td>
<td>2,313 (5,100)</td>
<td>33.5</td>
<td>42.0</td>
</tr>
<tr>
<td>50PAX</td>
<td>3,447 (7,600)</td>
<td>590 (1,300)</td>
<td>23.5</td>
<td>28.4</td>
</tr>
<tr>
<td>Military</td>
<td>8,392 (18,500)</td>
<td>1,724 (3,800)</td>
<td>33.4</td>
<td>33.6</td>
</tr>
</tbody>
</table>
7) The main assumption is that the gas density is the only parameter that governs the physical process of the wall-jet generation by the plasma discharge. A process of collisions between ions and neutral molecules creates the forces that result in the wall-jet. The collisions are governed by the mean-free-path and the number of molecules in a unit volume. Therefore, with the assumptions listed above, the gas density in laboratory tests should be set to be equal to the density at the actuator location in flight conditions.

Figure 2: Schematics of four engine models. (a) 300 PAX, (b) 150 PAX, (c) 50 PAX, (d) Military. HPC is high-pressure compressor, HPT is the high-pressure turbine, LPT is the low-pressure turbine.
Assessment of the validity of these assumptions and possible subsequent refinements are a subject for future work. With these assumptions, the main factor affecting the induced jet dependence on pressure and temperature is captured by considering only the density.

Validation of the assumption that temperature affects only the density is not trivial. It is known that some of the reactions between different charged molecules and electrons in the plasma are temperature dependent. Usually the dependence is weak, except for the temperature dependence of electron attachment processes, which can be significant above 1000 K (1800 °R). Experimental validation involves setting up heating in vacuum and pressure chambers, which is a technical challenge, and developing diagnostic techniques. These difficulties motivated the work reported here. It seems that the only practical approach to assess the full effect of temperature and pressure on the momentum transferred to the fluid is to use numerical simulation of the DBD plasma actuator at different temperatures and pressures. This simulation is challenging and is planned to be performed in the future. The authors are not aware of any reported work on this topic.

The assumption that the temperature affects only the density is very reasonable for temperatures under 1000 K (1800 °R). The open question is whether it is significant at higher temperature levels. If it turns out to have a large effect, it is expected to affect the calculated test conditions only for turbine engine applications in the combustion chamber and the high-pressure turbine, which are at temperatures higher than 1000 K (1800 °R), as seen in Figure 3 for the 300 PAX engine, and in the temperature figures in [65] for the other engine classes. Validation of the density matching hypothesis for a limited range of temperatures based on published experimental data is reported in a separate section below.

**Test-chamber pressure**

The chamber pressure and temperature to yield the same density as in flight are calculated as follows:

The gas density in the laboratory test chamber should be the same as the density at the application flight conditions,

\[ \rho_c = \rho \]  

(1)
where subscript $c$ indicates conditions in the chamber.

Assuming an ideal gas of a fixed species, and therefore with constant $R$,

$$\rho = \frac{P}{RT}$$  \hspace{1cm} (2)

the following relationship is obtained

$$P_c = \frac{P}{T/T_c}$$  \hspace{1cm} (3)

where

$P_c$, $T_c$, $\rho_c$ – Laboratory chamber pressure, temperature, and density.

$P$, $T$, $\rho$ – Static pressure, temperature, and density at flight conditions

**Test-chamber pressures for air vehicles**

The chamber pressures $P_c$ were calculated first for the case of an air vehicle (Figure 9). An air vehicle is flying at altitude $h$ at Mach number $M_{\infty}$. The atmospheric pressure at altitude $h$ is $P_{\text{atm}}(h)$ and the temperature is $T_{\text{atm}}(h)$, and are given by Standard Atmosphere tables. The local Mach number at the actuator location is $M$, which can be larger or smaller than $M_{\infty}$, depending on the flow development on the body, as determined by its geometry and flight conditions. We assume isentropic flow without shock waves. Using isentropic relationships at the freestream and at the actuator placement location with common stagnation conditions, and taking the atmospheric conditions at altitude $h$ as the static conditions, we obtain:

$$P_c = \frac{T_c P_{\text{atm}}(h)}{T_{\text{atm}}(h) f(M)}$$  \hspace{1cm} (4)

where

$$f(M) = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{-\frac{1}{2}}$$  \hspace{1cm} (5)
Figure 5: 300 PAX engine – static and total (stagnation) densities. (a) Core flow-path, (b) Bypass flow-path.

Figure 6: 150 PAX engine – static and total (stagnation) densities.
The chamber pressures for the following special cases are:

1) Actuator placed on a stationary vehicle at altitude $h$: $M_\infty = 0, M = 0$

Therefore $f(M_\infty) = 1, f(M) = 1$, and we obtain from eq. (4),

$$P_c = \frac{T_c}{T_{atm}(h)} P_{atm}(h)$$

This result is expected, as the static density on a stationary vehicle is the same at the atmosphere density.

2) Actuator placed on a flat plate at altitude $h$ at zero angle of attack: $M_\infty = M$

We obtain from eq. (4) the same relationship,

$$P_c = \frac{T_c}{T_{atm}(h)} P_{atm}(h)$$

This result is also expected, as the static conditions are the same as the atmospheric conditions.

3) Actuator placed at the stagnation point (as is common for flow control of airfoil leading-edge stall):
M = 0, and we obtain from eq. (4)

\[ P_c = \frac{T_c}{T_{atm}(h)} \frac{1}{f(M_{\infty})} \]  \hspace{1cm} (7)

The chamber pressure \( P_c \) is shown in Figure 9 as a function of altitude for the first two cases (eq. (6)), and for flight Mach numbers \( M_{\infty} = 0.5 \), with local Mach numbers of \( M = 0 \) (stagnation point) and \( M = 0.8 \) (eq. (4)). A curve for \( M_{\infty} = 1 \) with local Mach number of \( M = 0 \) (stagnation point), representing an extreme case, is also shown. An example of a flow with shocks is also presented in Figure 9, for an actuator placed behind the oblique shock wave on a 20° wedge at \( M_{\infty} = 2 \). Isentropic conditions were assumed upstream and downstream of the shock, and oblique shock relations were used to calculate the flow conditions on the wedge surface downstream of the shock.

The calculations are relatively straightforward for the shown simplified air vehicle cases. Obtaining the density at the placement location of actuators in actual configuration and flow conditions will involve obtaining data from CFD or measurement, taking into account viscosity and non-isentropic flows.

**Test-chamber pressures for turbine engines**

The situation for gas turbine engine application is more complex than for air vehicles because of the turbomachinery components and the combustion processes. The test-chamber pressures needed for turbine engine applications were calculated from the engine model data for the four generic engine classes. In these calculations, sea-level pressure was 101.3 kPa (14.7 psi), and sea-level temperature (hot day) was 29.8°C (545.7 °R). The latter was also taken as the value of the chamber room temperature. The results are displayed in Figures 10–13. They show the test chamber pressure at room temperature that will yield a chamber density equal to the density at each axial station of the engine. Some notes on the calculations are provided in the discussion section.

**Validation of density matching hypothesis**

We have used published data to validate the density matching hypothesis. The data is taken from two experiments. The first is Benard et al. [52], who report results of
Figure 10: 300 PAX engine – chamber pressure. (a) Full scale plot, (b) Enlargement of (a).

Figure 11: 150 PAX engine – chamber pressure. (a) Full scale plot, (b) Enlargement of (a).
Figure 12: 50 PAX engine – chamber pressure. (a) Full scale plot, (b) Enlargement of (a).

Figure 13: Military engine – chamber pressure. (a) Full scale plot, (b) Enlargement of (a).
experiments in a test chamber at room temperature with pressure varying from 20.3 to 101.3 kPa (0.2 to 1 atm). The case used was for applied voltage of 15 kV and a frequency of 1 kHz ([52]: Figure 5(b)). The second experiment is by Benard and Moreau [57] reporting test results of a DBD actuator in an altitude chamber. The pressure and temperature were varied simultaneously to simulate ascending from sea level to about 10,058 m (33,000 ft). The corresponding pressure varied from 101.3 to 26.3 kPa (1 to 0.26 atm), and the temperature varied from 288 to 228 K (518 to 410 °R). The voltage was 14.5 kV and the frequency 1.5 kHz. The data available in those papers is the plasma region extent (the distance of the plasma region from the exposed electrode), which is related to the aerodynamic performance of the actuator. We calculated the density from the values of pressure and temperature at the data points in those two experiments assuming ideal gas. The plasma extent is plotted against density for these two experiments as shown in Figure 14.

As can be seen from the figure, the curves are quite close to each other. This result is very encouraging, as it shows that at least for the range of pressures and temperatures of these experiments the density matching seems to be valid. It must be noted that the two experiments were not at exactly identical applied voltage conditions and also the actuators differ in some geometrical details. We have qualitatively assessed the differences and concluded that the differences in geometry are compensated by the differences in applied voltage and frequency, hence there is justification for using these two cases for comparison and validation.

In the tests performed by Benard et al. [58] with NS-DBD actuator (nanosecond-pulsed DBD or NP-DBD in their terminology) they found that density is a good scaling parameter except at low temperatures (-50°C) due to the reduced permittivity of the dielectric material (polyamide) at low temperature. The temperature range in [58] was 20°C to -50°C, hence it looks promising that the density matching principle may be applicable for actuators other then AC-DBD over higher range of temperatures.

Discussion

For the air vehicle application, the chamber pressures decrease with altitude according to the variation of density with altitude and local flow conditions at the actuator location. The situation is more complex for the turbine engine. The results show that the test-chamber pressure varies greatly across the different engine classes, from sub-atmospheric to above atmospheric pressures, depending on the operating conditions and location of the actuator in the engine. For example, if a DBD plasma actuator is to be placed at the inlet to the high pressure turbine for the 300 PAX engine, it must be tested at 608 kPa (6 atm) if it is intended to operate at sea-level takeoff conditions, and at 294 kPa (2.9 atm) if it is intended to operate at 10,668 m (35,000 ft) cruise. If it is to be used in the exit of the high-pressure compressor duct (burner inlet), it must be tested at 1256 kPa (12.4 atm) at takeoff conditions, and at 628 kPa (6.2 atm) at 10,668 m (35,000 ft) cruise conditions. If it is to be used at the low-pressure turbine exit, it must be tested at 51 kPa (0.5 atm) for operation at takeoff, and at 20 kPa (0.2 atm) at cruise. If the actuator is to be placed on the low-pressure turbine of the 50 PAX engine flying at 19,812 m (65,000 ft), its performance must be tested at a very low chamber pressure of 3 kPa (0.03 atm).

Note that the calculations are based on conditions at the inflow and outflow planes of the various engine components. The calculated points are connected with straight lines. Further refinement is needed to account for local flow conditions inside the component. For example, in turbomachinery there are inter-row and inter-stage variations, and in inter-blade passages there is acceleration or diffusion or even shock waves that will modify the results. Those local modifications are not included in this study and are left for future work.
Note also that the results shown in Figures 10–13 display the chamber pressures based on total (stagnation) as well as static conditions in the engine. The reason that the results corresponding to total conditions are shown is that the total conditions are equal to static conditions at locations where the velocity is zero, corresponding to placement of the actuator at locations such as the leading edge of a turbine or compressor airfoil. As can be seen in the figures, the differences are not large.

Additional insights can be gained from the distribution of the unit Reynolds number [65], not included here due to space limitations. Usually, a low unit Reynolds number may indicate flow separation. For example, it is known that there is a tendency for flow separation on the low-pressure turbine (LPT) suction surface at altitude. Low Reynolds number locations are good candidates for implementation of active flow control. However, those locations are also characterized by low density, requiring the plasma actuator to be tested at low chamber pressures. DBD plasma actuators may suffer from loss of performance as the density is decreased (note that there are insufficient and conflicting results in the published literature on this matter). Therefore, laboratory testing is critical for establishing that the DBD actuators can perform adequately under low density conditions.

It is important to note that for research in the field of weakly ionized plasma, laboratory experiments were traditionally performed in a vacuum chamber at room temperature. It therefore became common in that field to specify the chamber pressure as an experimental parameter. This may have led to habitually considering the pressure, rather than the density, as the relevant parameter.

The density matching assumption has implication also to wind tunnel testing. When a model is tested in wind tunnels, similarity of Mach number and Reynolds number is observed. When the test model includes an AC-DBD flow control device, density similarity should also be observed to ensure the actuator performance is correctly accounted for. Usually when Mach number and Reynolds number are set in a wind tunnel, the density cannot be independently controlled unless it is a pressurized closed-circuit tunnel or a blow-down open-circuit tunnel. Hence attention to the performance of the actuator during the wind tunnel testing is needed. Similar consideration should be applied also to testing of turbomachinery in rotating rigs.

Concluding remarks

The work presented here was motivated by DBD plasma researchers who had an interest in focusing their experimental and computational research to the range of operating pressure and temperatures that would be encountered in practical applications of DBD actuators in the flight envelope of air vehicles and turbine-engines. The corresponding data were provided with focus on the density which was proposed to be the significant DBD performance parameter.

Data on density distribution in four generic turbine engines, representing four different thrust classes, were presented. The complete data sets, including temperature, pressure, Mach number, velocity, and unit Reynolds number are presented in [65]. These non-proprietary data are useful for various applications related to formulating test conditions of flow control devices placed in various engine components.

Testing at room temperature is significantly easier than testing at high temperatures, therefore the density data were used to develop test conditions for characterization of DBD plasma actuators in a chamber at room temperature. The underlying assumption is that the performance of DBD actuators depends only on the density and that all other temperature-related effects are negligible over the temperature range existing in the turbine engine. Based on this assumption, and the engine models’ data, the required test-chamber pressure at room temperature for simulating in-flight engine operating conditions was calculated. The test chamber pressures vary with the location of the actuator in the engine, the type of engine, and the flight operating conditions. There is a wide spread in the pressure range, depending on the specific application, varying from 1256 to 3 kPa (12.4 to 0.03 atm) for the four engine classes’ models and the flight conditions studied.

Chamber pressures needed to test DBD actuators for air vehicles at room temperature were also shown. Unlike the engine environment, the flow conditions for testing flight vehicles can simply be calculated with data readily available from standard atmospheric tables for any flight speed and altitude. Modifications can be added to account for local flow conditions at actuator placement.

The test pressures presented rely heavily on the density matching assumption. Deviation from this assumption is not expected to be large, and it is believed that the results are correct to at least first order. The density
matching assumption has implication also to wind tunnel testing. Similarity of Mach number, Reynolds number should be accompanied by density similarity when AC-DBD actuators are tested.

Nomenclature

\[ 
\begin{align*}
H, h & \quad \text{Altitude (m)} \\
M & \quad \text{Mach number} \\
P & \quad \text{Static pressure (Pa)} \\
R & \quad \text{Gas constant (kg m}^2/\text{s}^2/\text{K)} \\
Rey & \quad \text{Reynolds number} \\
T & \quad \text{Static temperature (K)} \\
V & \quad \text{Velocity (m/s)} \\
X & \quad \text{Axial distance along the engine (m)} \\
\rho & \quad \text{Density (kg/m}^3) \\
\end{align*} 
\]

Subscripts

\[ 
\begin{align*}
c & \quad \text{Conditions in chamber} \\
\infty & \quad \text{Freestream conditions} \\
\text{atm} & \quad \text{Atmospheric conditions} \\
\end{align*} 
\]

Acronyms

- DBD: Dielectric Barrier Discharge
- HPC: High Pressure Compressor
- HPT: High Pressure Turbine
- LPC: Low Pressure Compressor
- LPT: Low Pressure Turbine
- PAX: Passengers

References


