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On the mechanical efficiency of dielectric barrier discharge plasma actuators

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The mechanical power production and electrical power consumption of the dielectric barrier discharge plasma actuator is investigated for different operating conditions. The ratio of these two values delivers the mechanical efficiency of the actuator as a flow acceleration device. The general trend is that higher carrier frequencies and voltages lead to higher values of the efficiency. The values that were found for the mechanical efficiency are very small, the highest recorded value is only 0.18%. © *2011 American Institute of Physics*. [doi:10.1063/1.3597652]

Over the past years, plasma actuators have received a significant amount of attention from the flow control community. Mainly because they are easy to manufacture, contain no moving elements, and can be mounted (nearly) flush with the surface. The specific actuator that is investigated in this letter is the dielectric barrier discharge (DBD) plasma actuator. Its main components are two electrodes and a layer of dielectric material between these electrodes, schematically presented in Fig. 1. For the current study the geometrical layout is kept the same during all the experiments. The geometrical parameters of this configuration can be found in Table I and the exact setup is discussed in Ref. 1. A good introduction into the working principles of the DBD plasma actuator can be found in Ref. 2.

This letter forms an extension on the work that was carried out in Ref. 1. That study focused on deriving an accurate model of the body force distribution that is exerted by the plasma actuator on the flow. The effects of changing the input voltage and frequency on this body force distribution were determined. For the high-voltage (HV) signal a sine wave form was used, specified by its carrier frequency f_{ac} and peak-to-peak voltage V_{app}. The frequencies and voltages that were used can be found in Tables II and III, respectively.

There are basically two ways to obtain the body force distribution that is produced by the plasma actuator. One option would be to model and simulate the underlying physics of the ionization process.[3] The other option is to implement the actuator in an experimental setup and from the recorded velocity fields back calculate the body force distribution. The latter approach was chosen in Ref. 1, where high speed particle image velocimetry (PIV) experiments were carried out. Using a postprocessing technique based on the Navier–Stokes equations it was then possible to derive a spatially resolved distribution of the body force. A visualization of the body force distribution is shown in Fig. 2 for the case of $V_{app}=12\ \mathrm{kV}_{pp}$ and $f_{ac}=2$ kHz. The contour lines show the strength and extent of the body force and the black arrows indicate the direction in which the force is operating. The gray arrows present the steady-state velocity field and the gray rectangles are used to indicate the location of the plasma actuator.

The study from Ref. 1 delivered both the velocity field and the two-dimensional body force field. All the data are, therefore, available to calculate the mechanical power P_{out} that is produced by accelerating the flow. This can be done by means of Eq. (1)

$$P_{out} = \int_{\Omega} \mathbf{F}_b \times \mathbf{V} d\Omega, \qquad (1)$$

where Ω is the integration region around the plasma actuator, F_b is the body force, and V the velocity. So, Eq. (1) comes down to taking the inner product of the body force and the velocity field in Fig. 2.

The body force distribution does not change in time and the PIV measurements from Ref. 1 were carried out at a high sampling frequency of 10 kHz. It is, therefore, possible to accurately track the development of the produced power P_{out} in time. Figure 3 presents the case where the plasma actuator is operated at a voltage of $12\ \mathrm{kV}_{pp}$ and a frequency of 2 kHz. It takes about 6 ms for the power output to reach a quasisteady level of approximately 12 mW/m of actuator length. Changing the input voltage and frequency of the plasma actuator does not have a profound effect on the settling time that is recorded. For all cases that were tested, a settling time of about 6 ms was recorded.

The electrical power consumption P_{in} is calculated based on instantaneous readings of voltage and current during actuation. Voltage is measured directly from the HV amplifier while current is measured using a known resistance (100 Ω) between the grounded electrode and the ground cable. By measuring voltage across the resistance, traveling current can be calculated. Both voltage and current signals are acquired using an A/D card with sampling frequency of 100 kHz. Data acquisition is performed for 3.5 s during actuation.

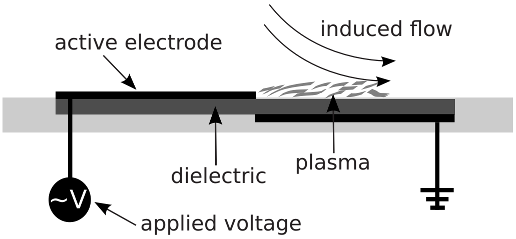

FIG. 1. Configuration and operation of the DBD plasma actuator.

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TABLE I. DBD configuration parameters.

Parameter	Value
Active electrode length (mm)	10
Grounded electrode length (mm)	10
Dielectric thickness (μm)	100
Active electrode thickness (μm)	100
Grounded electrode thickness (μm)	60
Horizontal gap between electrodes (mm)	0

TABLE II. The power consumed P_{in} and produced P_{out} by the plasma actuator and its efficiency η for a range of different operating voltages.

V_{app} (kV$_{pp}$)	f_{ac} (kHz)	P_{in} (W/m)	P_{out} (W/m)	η (%)
8	2	6.1	7.86×10^{-4}	1.30×10^{-2}
10	2	10.0	3.09×10^{-3}	3.09×10^{-2}
12	2	15.2	1.16×10^{-2}	7.65×10^{-2}
14	2	21.9	2.48×10^{-2}	1.14×10^{-1}
16	2	30.2	5.51×10^{-2}	1.83×10^{-1}

TABLE III. The power consumed P_{in} and produced P_{out} by the plasma actuator and its efficiency η for a range of different carrier frequencies.

V_{app} (kV$_{pp}$)	f_{ac} (kHz)	P_{in} (W/m)	P_{out} (W/m)	η (%)
10	1	5.1	1.72×10^{-3}	3.41×10^{-2}
10	2	10.1	3.09×10^{-3}	3.07×10^{-2}
10	3	14.8	7.78×10^{-3}	5.25×10^{-2}
10	4	19.0	1.93×10^{-2}	1.02×10^{-1}

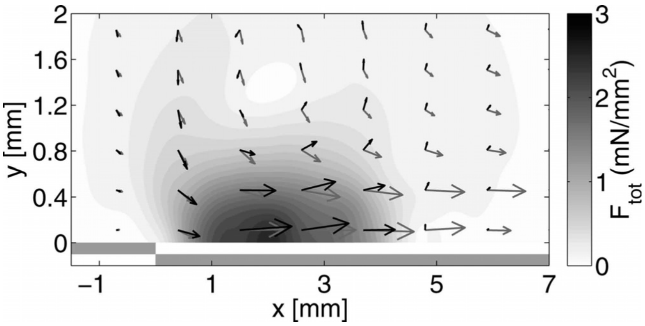

FIG. 2. The body force and the velocity field (t=15 ms) for the case of V_{app}=12 kV$_{pp}$ and f_{ac}=2 kHz. The gray vectors indicate the velocity field and the black vectors the body force.

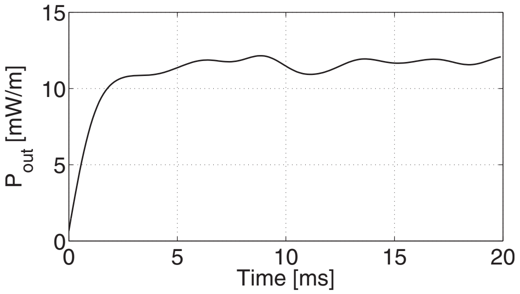

FIG. 3. The power produced by the actuator as a function of time. For the case that V_{app}=12 kV$_{pp}$ and f_a=2 kHz.

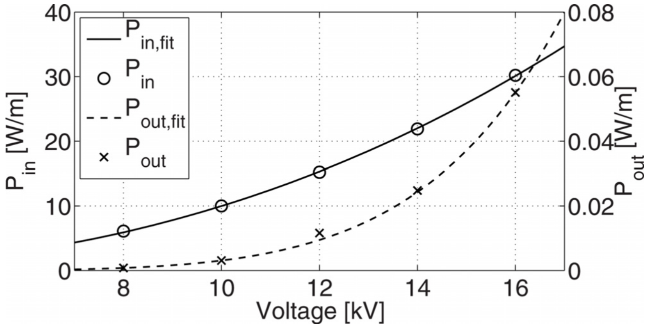

FIG. 4. The power consumed P_{in} and produced P_{out} by the plasma actuator for a range of voltages.

It must be stressed here that DBD discharge current is typically governed by a multitude of high frequency peaks corresponding to the microdischarges in the plasma region during the avalanche ionization phase.[4] These microdischarges occur in microsecond time scales and cannot be accurately measured independently of electromagnetic noise due to the high electric field. For this reason the acquisition is performed for a large time period of 3.5 s in order to alleviate errors from under resolving the discharge current. For the power consumption P_{in}, the instantaneous voltage and current signals are multiplied and the result is averaged to produce the final value for P_{in}.

So, together with the produced power P_{out}, all the information is available to calculate the mechanical efficiency η of the plasma actuator. The mechanical efficiency is defined as the ratio between the produced power P_{out} and the consumed power P_{in}. The relation between the consumed and produced power and the voltage and frequency is shown in Figs. 4 and 5, respectively, and the results of the efficiency calculations are depicted in Fig. 6.

Previous investigations[4] showed that the consumed power can be related to the applied voltage by means of the following power law: $P_{in}\sim V^n$. In Ref. 4 a value of n=3.42 was found at an operating frequency of 6 kHz and for an operating frequency of 3 kHz a value of n=3.35 was found. The same fitting function can also be applied to the data of the current research project and results in a good fit, as can be seen in Fig. 4. The standard deviation between the fit and the consumed power is 0.4% of the power that is consumed at a voltage of 16 kV$_{pp}$. Although the fit is of a good quality, the value that is found for the exponent $n_{P_{in}}$ is only 2.35. This is significantly smaller than the values that were found in Ref. 4. This can be due to the fact that the geometrical layout of the actuator that is used in Ref. 4 is different from

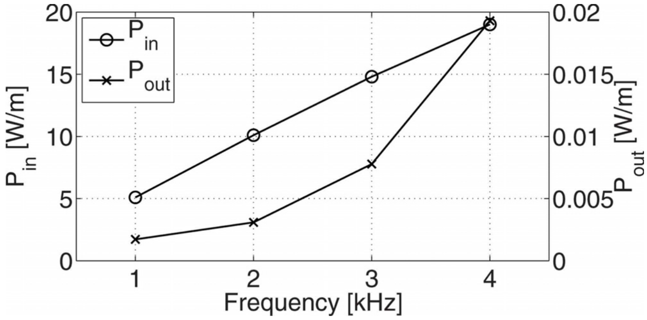

FIG. 5. The power consumed P_{in} and produced P_{out} by the plasma actuator for a range of frequencies.

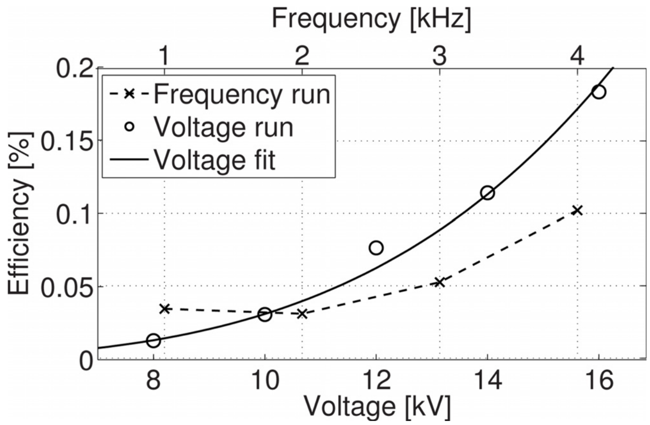

FIG. 6. Efficiency as a function of the frequency f_{ac} and voltage V_{app}. For the frequency run the voltage is kept at a fixed value of 10 kV_{pp} and for the voltage run the frequency is kept at a fixed value of 2 kHz.

the one used in this project. Furthermore, the operating conditions are also different. Lower voltages and higher frequencies were used in Ref. 4.

The same fitting function can also be used for the produced power and the efficiency, in both cases reasonably accurate fits are obtained. The standard deviation equals 1.69% and 3.86%, respectively, these values are normalized with the maximum values that were recorded for the produced power and the efficiency. For the produced power, a high value of $n_{P_{out}}=6.13$ is found and for the efficiency $n_\eta=3.82$. Note that $n_{P_{out}}-n_{P_{in}}=6.13-2.35=3.78\approx n_\eta$, which demonstrates the quality of the fit.

The relation between the power/efficiency and frequency is shown in Figs. 5 and 6, respectively. The consumed power varies approximately linear with the carrier frequency and the produced power cannot be accurately approximated by means of a power law relation. For the efficiency it is interesting to note that it is not a monotonically increasing function, rather it exhibits a minimum at 2 kHz. This behavior also cannot be approximated by means of the power law relation from Ref. 4.

So, from the point of view of mechanical efficiency it seems beneficial to operate at a high voltage and/or high frequency. This will, however, reduce the lifespan of the plasma actuator and introduce a stronger body force in the flow.[1]

Another important point to be noticed is the magnitude of the mechanical efficiency, which is very small. The largest value that is found is 0.183%, for the case where the actuator is operated at a voltage of 16 kV_{pp} and a frequency of 2 kHz. The smallest value for the efficiency is only 0.013%, for a voltage of 8 kV_{pp} and a frequency of 2 kHz. This low mechanical efficiency, however, does not imply that the DBD plasma actuator is not effective as a flow control device.

Although it is interesting to analyze the actuator from the point of view of its mechanical efficiency, it is not the only measure of efficiency. In its role as a flow control device the main question is how effective it is in exciting/damping certain flow structures. In that role the DBD plasma actuator has already proven itself. In Ref. 5 it is, for instance, used to damp artificially introduced Tollmien–Schlichting waves. High attenuation rates are reached, which, in turn, produce a significant drag reduction. So, although the mechanical efficiency as defined in this letter is very low, its efficiency as a flow control device can still be excellent.

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