# On Performance and Efficiency of Dielectric Barrier Discharge Plasma Actuators for Flow Control Applications

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Received date 19th September 2012; Accepted date 20th December 2012

**ABSTRACT**
With further maturity and applicability of plasma actuator flow control it becomes increasingly important to classify and quantify the net efficiency of plasma actuators, taking into account their effect on the flow and including a careful analysis and evaluation of the corresponding energy requirements. The present work provides such an evaluation standard with a comprehensive discussion of plasma actuator performance and efficiency. Existing evaluation strategies are reviewed, contradictory definitions presently found in the literature are clarified, and all discussed quantities are ordered into a universal power-flow diagram, serving as a guideline to classify and quantify plasma-actuator performance in flow control applications.

## 1. INTRODUCTION

In recent years, discharge-based flow control actuators have proven to be an attractive and promising alternative to conventional flow-control devices, as comprehensively discussed by Cattafesta and Sheplak [1], Moreau [2] or Corke et al. [3]. However, despite their increasing usage and popularity '*a widely accepted standard for plasma actuators does not exist*', as recently observed by Little et al. [4]. Obviously, independent of the individual flow control application, there is a need to classify and quantify the effect of plasma actuators on the flow allowing also quantitative comparisons between different hardware realizations in different laboratories. Furthermore, a more unified nomenclature for the performance characterization of such devices would help reduce confusion, often arising when currently comparing different studies in the literature.

The present work makes a suggestion how to meet these goals of a common evaluation standard.

## 2. PERFORMANCE CHARACTERISTICS

The basis for a robust quantification of the plasma-actuator performance is the identification of convenient measures appropriate to characterize various stages of their energy requirements. Roth and Dai [5] introduced a power-flow diagram, which considers reactive power, dielectric heating and plasma maintenance, phenomenologically summarizing the power losses inevitably accompanying plasma actuator operation. To use such a power-flow curve, quantitatively measurable quantities have to be defined for each of the intermediate power stages.

In the present work the power flow concept first introduced by Roth and Dai [5] has been significantly extended, comprising in total four individual stages to characterize the performance of plasma actuators for flow control applications. The resulting power-flow diagram is sketched in Figure 1, which also contains the corresponding efficiency chain. These four power stages will first be described in general before more practical definitions are introduced in Section 3.

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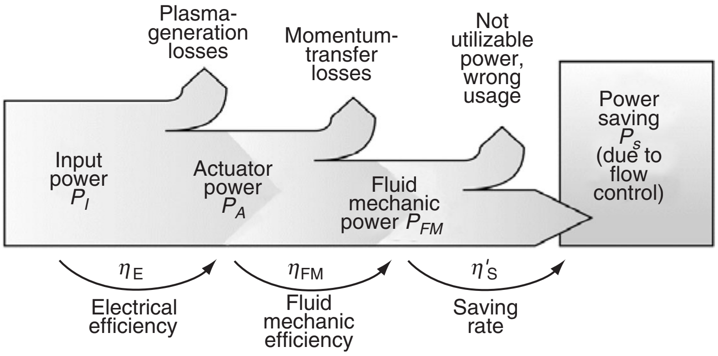


Figure 1. Power-flow diagram of plasma-actuator operation.

Any discharge-based control device requires an energy source delivering an electrical *input power* $P_I$ to the chosen HV transformer. Many research groups use commercial laboratory power supplies as a voltage source, but (rechargeable) batteries are essential when thinking about flow control of drones or other unmanned aerial vehicles (UAVs). In such cases the energy source involves additional weight of the aerial vehicle and subsequently needs to be considered for overall efficiency and effectiveness calculations.

Not all of the supplied electrical input power $P_I$ is available to influence the flow, since additional losses occur due to reactive power, dielectric heating and plasma maintenance, leaving only the electrical *actuator power* $P_A$ consumed by the plasma actuator at the discharge region. The difference, i.e. $P_I - P_A$ represents the power flow through a plasma actuator and has been thoroughly discussed by Roth and Dai [5], in fact their discussion is mainly restricted to this very first stage ($P_I \rightarrow P_A$) of the power-flow diagram. The actuator power $P_A$ is of course a key quantity for any discharge application (see Manley [6] or Kogelschatz [7]) and moreover, Kriegseis et al. [8] show how this quantity can be precisely measured, even online as a monitoring quantity [9].

Independent of the flow-control application, the momentum transfer from the discharge to the air results in a modified airflow, where generally the respective power supplied to the air can be characterized as the *fluid mechanic power* $P_{FM}$. However, the term 'momentum transfer' refers to a variety of measurement and (post-) processing strategies.

Flow manipulation can be measured either directly by means of high precision balances or implicitly through velocity measurements and subsequent force and power determination. Since velocity information is not available when using direct approaches (see e.g. Gregory et al. [10] or Kriegseis et al. [11]), this measurement technique only allows the resulting integral value of the actuator thrust $T$ instead of force $F$ or power $P_{FM}$ to be specified.

Velocity information based determination of the momentum transfer can be divided further into integral and differential methods as comparatively analyzed by Kriegseis et al. [12]. Based on the integral momentum or energy equation three different types of integral quantities can be determined. If only a wall-jet velocity profile downstream of the actuator is available, the corresponding momentum flux (see e.g. Hoskinson et al. [13]) or power flux (see e.g. Pons et al. [14]) can be determined. This power-flux determination and efficiency considerations pertaining to this flux are well-documented by Moreau [2].

Based on the velocity information that crosses an arbitrary control volume (CV) enclosing the discharge domain, the integral actuator thrust $T$ can be determined (see e.g. Kotsonis et al. [15] or Durscher and Roy [16]). Further consideration of the shear stress at the wall boundary gives rise to the actuator force $F$ (Versailles et al. [17]). Due to the no-slip wall condition, both CV- based approaches lead to identical results for the integral value for $P_{FM}$ (Kriegseis [18]). Since the flow acceleration inevitably involves self-induced drag (cp. Enloe et al. [19]), the force $F$ induced to the air is significantly ($\approx 30\%$) [12] higher than the resulting net thrust $T$ of the actuator. This fact confirms the necessity to carefully distinguish between the quantities $T$ and $F$.

In contrast to integral methods (e.g. CTA, LDA, Pitot tube), differential methods require data from whole-field techniques such as PIV. Based on the Navier-Stokes or vorticity equation the body-force distribution $f(x, y)$ can be determined, as proposed by Wilke [20] and Albrecht et al. [21]. Subsequent scalar multiplication with the underlying velocity field $u(x, y)$ and spatial integration leads to $P_{FM}$ (Giepman and Kotsonis [22]). The main contribution to the losses in this part of the power-flow diagram ($P_A \rightarrow P_{FM}$) arise due to light and sound emission as well as thermal heating of the air around the discharge.

The final step in the power-flow diagram, namely the overall *power savings* $P_S$ is not only the most difficult to define and/or measure, but is often also controversial. While for some applications, e.g. transition delay for drag reduction (Grundmann and Tropea [23]), such power savings can be easily estimated, in other situations the benefit of flow control can be completely non-energetic, for example, an increase in maneuverability of a UAV. Here flight performance improvements became more important than power savings. Another example is the optimization of plasma actuators in terms of flow control authority (e.g. Forte et al. [24] or Thomas et al. [25]), whereby the power imparted to the system is of minor importance.

Nevertheless, the power saving $P_S$ serves as a measure for the success of the flow-control efforts and represents the final step of the power-flow diagram. This final step has to be defined individually for the particular flow-control application. The (dis-)advantages of discharge based and conventional approaches of flow control are comparatively reviewed by Cattafesta and Sheplak [1]. Jabbal et al. [26] exemplarily estimated the individual flow control success of these different *flow control system architectures* for an Airbus A320 aircraft wing. The respective optimization strategies and corresponding losses ($P_{FM} \rightarrow P_S$) remain, however, highly dependent on the individual base flow scenario.

## 3. DEFINITION OF EFFICIENCIES

In the following section the measurability of the different power values; hence the feasibility of evaluating various power stage efficiencies is discussed. Note that the term *efficiency* $\eta$ is strictly defined as a non-dimensional value in the range $0 \leq \eta \leq 1$. Dimensioned coefficients and those that can exceed the value 1 are indicated by an additional asterisk ($\eta^*$) and apostrophe $\eta'$, respectively.

The efficiencies to be addressed in the following discussion have been noted in the power-flow diagram of Figure 1 and the necessity for choosing this particular grouping will become evident when discussing their measurability. However, the real value in distinguishing various power-stage efficiencies is to correctly identify the exact contribution of optimization efforts. This is easily illustrated and understood by simply surveying the large number of studies addressing specific factors of plasma actuator performance, including input parameters (energy source, HV transformer [8], applied waveform for discharge [27]), the geometrical arrangement of the actuator (length, width and thickness of electrodes and dielectric [28]), novel actuator configurations (floating electrode [29], electrode design [30] and quantity [31]) or environmental influences (weather conditions, state variables, flow speed [17, 32, 34]). The goal is to easily recognize where each of these influences fit into the power-flow diagram and how effective each is in improving the overall effectiveness.

The *electrical efficiency* $\eta_E$ is defined as the ratio of the two electric measures $P_I$ and $P_A$ according to

$$\eta_E = \frac{P_A}{P_I} . \tag{1}$$

$\eta_E$ is specified by the power losses occurring during plasma generation, which is dominated by internal heating of the chosen HV transformer and losses in the dielectric barrier. Kriegseis et al. [8] demonstrated that $\eta_E$ is not only affected by the properties of the power supply units but also depends on the properties of the load connected. Therefore, this efficiency can be optimized by appropriate impedance matching (Singh and Roy [34]) or proper choice of the dielectric material (Roth and Dai [5]). This efficiency is no doubt the easiest of all efficiencies to quantify.

In 1960 Robinson [35] defined the fractional efficiency of electrokinetic conversion for the electric wind of the corona discharge as the relation of the kinetic output power to the electrical input power. Based on this, the *fluid mechanic efficiency* can be defined as

$$\eta_{FM} = \frac{P_{FM}}{P_A} . \tag{2a}$$

Similar definitions have already been used e.g. by Giepman and Kotsonis [22], Janssen et al. [36], Jolibois and Moreau [37] or Léger et al. [38]. The main losses characterized by $\eta_{FM}$ arise from thermal radiation, chemical reactions and sound/light emission.

In cases when the fluid mechanic power $P_{FM}$ cannot be determined, a convenient and frequently applied replacement is the actuator thrust $T$ (e.g. Gregory et al. [10], Porter et al. [39], Enloe et al. [40]). Consequently, the actuator thrust $T$ is utilized to define a dimensioned measure of the *fluid mechanic effectiveness* as

$$\eta^{*}_{FM} = \frac{T}{P_A}\left[\frac{N}{W}\right]. \tag{2b}$$

Such a dimensioned coefficient has already been suggested by different authors. Ferry and Rovey [41] introduce the so-called 'actuator effectiveness'. Other authors (e.g. Gregory et al. [10], Hoskinson et al. [13, 28] and Porter et al. [39]) in contrast, refer to it as the 'force (production) efficiency' or simply keep the term 'thrust' (Enloe et al. [42]). The thorough distinction between efficiency and effectiveness according to (2a) and (2b) is very important in order to avoid confusion of nomenclature. Although both quantities ($T$ and $F$) are important characteristics for plasma actuators, application of the thrust $T$ and not a force $F$ in definition (2b) is strongly recommended, since $F$ only represents an intermediate state (due to self-induced drag); hence the comparability to directly measured thrust data is impossible.

The last link of the efficiency chain depends solely on the level of successfully conducted flow control. Although being a non-dimensional number, the *saving rate*

$$\eta'_s = \frac{P_s}{P_{FM}} \tag{3}$$

is not referred to as an efficiency, since it ideally exceeds the value of one.

The saving rate $\eta'_S$ has a wide range of possible physical interpretations, by which every flow-control application requires an individual definition of the governing quantity $P_S$ and consequently $\eta'_S$. Byerley et al. [43] and Rizzetta and Visbal [44], for instance, increase the operating efficiency of a turbine component by reducing or eliminating a separation (bubble) and reducing profile losses. Jukes and Choi [45] define $\eta'_S$ (referred to as 'power saving ratio') as the ratio between power savings due to drag reduction and the fluid mechanic power imparted to the flow.

An accurate determination of $\eta'_S$ is a challenging and complex task. This is illustrated easily by considering the use of plasma actuators on a UAV. Any modification of the flow-control device inevitably involves changes in the flight mechanics of the UAV. Increasing the discharge intensity of the plasma actuator, for instance, requires larger batteries and/or larger high-voltage transformers. Consequently the centroid of the entire vehicle is changed, which can then significantly influence the maneuverability of the UAV. Therefore, any optimization of such applications has to consider weight and geometry issues, as well.

The sensitivity of $\eta'_S$ in terms of drag reduction is emphasized by the work of Grundmann and Tropea [23]. They achieved considerable transition delay by means of plasma actuators only for a particular electrode arrangement. In subsequent diagnostics of the velocity field immediately surrounding the actuator, Kriegseis et al. [46] identified adverse/favorable flow patterns to be responsible for the failed/successful transition delay under otherwise constant operating conditions, i.e. power consumption of the applied flow-control device. An additional good example illustrating the difficulty in quantifying $\eta'_S$ is given by Jolibois and Moreau [37], where the chordwise actuator location on a profile is identified as a key factor for successful separation control (at constant actuator power $P_A$).

Finally, the quantification of the saving rate $\eta'_S$ can be further complicated by the fact that actuators can be used in many different configurations, depending on the effect desired. While often DBD actuators have been used to impart momentum in a steady manner as a wall jet, other configurations create streamwise vortices [47, 48] or localized momentum influx, e.g. through segmentation [49, 50], non-uniform configurations [30] and jet vectoring [51, 52]. Additionally, these actuators are often driven in an unsteady mode [53, 54], all of which may influence what governing quantity $P_S$ is to be used.

In summary, the three (efficiency) coefficients (1–3) yield an overall effectiveness of the DBD plasma actuator as a flow-control device according to

$$\eta'_{FC} = \eta_E \eta_{FM} \eta'_S. \tag{4}$$

To exceed the break-even point of the energy-balance, $\eta'_{FC} > 1$ is desired, i.e. plasma-actuator operation results in a net energy saving.

## 4. CONCLUDING REMARKS

In order to advance beyond simple feasibility studies towards practically relevant applications of plasma actuators, classification and quantification of all involved physical phenomena in terms of performance steps becomes necessary. The increasing need to compare existing actuator designs, geometric configurations and respective efficiency and effectiveness between different research groups demands such a framework [4, 8]. The present work meets this essential requirement with a discussion about classification and quantification of plasma actuator performance and corresponding efficiency. A power-flow diagram and the corresponding efficiency chain are presented, covering the power flow from the energy source to the achieved savings due to successful flow control. In conclusion, the present work introduces a common nomenclature and guidelines of performance classification within the community of discharge-based flow control research.

## ACKNOWLEDGEMENTS

The authors gratefully acknowledge financial support by the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) under grant EXC 259.

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