Renewable Energy 42 (2012) 105–110

Contents lists available at SciVerse ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Mitigation of flow separation using DBD plasma actuators on airfoils: A tool for more efficient wind turbine operation

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ARTICLE INFO

Article history:
Received 4 March 2011
Accepted 2 September 2011
Available online 23 September 2011

Keywords:
Plasma actuator
PIV
Separation control
Wind turbine
Particle image velocimetry

ABSTRACT

In this study, dielectric barrier discharge plasma actuators (DBD-PA) were used to actively control flow separation over a NACA0024 airfoil. Experiments were conducted at a free stream velocity up to $U \approx 10$ m/s ($Re \approx 1.3 \times 10^5$) in an open-circuit blower type wind tunnel with a test section measuring 200 mm × 200 mm × 600 mm. The airfoil model was designed specifically to incorporate minimum flow disturbances from the components of the DBD-PA and was made using rapid prototyping. A sheet of dielectric polyimide (125 μm) with copper electrodes (35 μm) was attached to the outer surface of the airfoil. A layer of DBD plasma across the airfoil was produced when a peak-to-peak voltage of $V_{p\text{-}p} = 8.0$ kV was applied between top and bottom electrodes at a frequency of $f_p = 9.0$ kHz. This development of plasma produced a tangential air jet across the surface of the airfoil, which reached its maximum value ($u_{j\text{-}max}$) in the range of $0.5 \text{ m/s} < u_{j\text{-}max} < 0.7$ m/s. Varying degrees of separation flow control was observed under these conditions. Performance comparisons were made between electrodes located at the leading edge (LE) and the quarter chord (QC, 25% of chord length) at angles of attack of $\alpha = 8°, 12°, 16°$. The plasma-induced jet velocities and flow profiles were measured using particle image velocimetry (PIV). Characteristics such as power consumption, voltage waveform, and current magnitude were quantified through the use of a digital oscilloscope.

1. Introduction

The World Wind Energy Association estimates that by the end of 2010, the global wind energy capacity will reach 200 GW [1]. Continued growth in this field has resulted in technological improvements in terms of blade designs, manufacturing methodology, and installation techniques. Each improvement is an effort to exploit all feasible methods in order to maximize efficiency, reduce cost, and increase power generation. The performance of the wind turbine blade is among the most important components in this system. However, conditions such as unstable wind can have a detrimental impact on power generation [2]. In the past, implementing mechanical devices such as leading edge and/or trailing edge flaps has helped improve turbine efficiency and control. While these systems have shown performance enhancement, they also increase mechanical complexity and structural weight [3]. Thus, as wind turbines continue to get larger, there is a strong demand for an alternative to flow control. For example, flow detachment over a wind turbine blade leads to increased pressure drag. The result is the degradation of the wind turbine's ability to produce electricity. The ultimate goal of our research is to provide a reliable and economically feasible means to control flow detachment over a wind turbine blade.

Dielectric barrier discharge plasma actuators (DBD-PAs) have displayed great promise in this field. DBD-PAs are composed of a dielectric layer sandwiched between an upper and lower electrode. Once a high enough voltage is applied across the two electrodes at radio frequencies, a layer of plasma is formed [4]. Manipulation the flow field takes place when this plasma produces a tangential air jet over the airfoil. This phenomenon is also referred to as "ionic wind" [2]. In contrast to their mechanical predecessors, very little weight is added to the system since DBD-PAs are electrical in nature.

Ionic wind has demonstrated flight control, lift enhancement, separation control, and drag reduction in previous research [5–15]. A promising application of DBD-PAs is separation flow control on wind turbine blades. When air becomes detached over the surface of an airfoil, the pressure gradient between the upper and lower

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doi:10.1016/j.renene.2011.09.001

Nomenclature

A	airfoil wetted area
c	chord length
C_L	coefficient of lift
d	thickness of dielectric material
E	peak power consumption of electrode
f_p	frequency of burst signal
L	lift force
P_{eff}	plasma effectiveness
$u_{j\text{-}max}$	maximum velocity of flow induced by DBD-PA
U	free stream velocity
U_{pOFF}	averaged free stream velocity in *plasma off* condition
U_{pON}	averaged free stream velocity in *plasma on* condition
v	kinematic viscosity
V_{p-p}	peak-to-peak voltage applied between top and bottom electrodes
α	angle of attack
$\sum'$	relative permittivity of dielectric
ρ	air density

surfaces decreases. Therefore, a wind turbine blade loses its ability to extract energy from the surrounding system, resulting in lowered power generation. Consequently, the research presented in this paper will deal exclusively with the mitigation of flow separation. The target wind turbine systems for this research are on the order of 1 kW–10 kW due to the characteristics of the DBD-PAs and range of Reynolds number (3.2×10^4– 1.3×10^5) explored in these experiments.

2. Experimental setup

For these experiments, a thin sheet of polyimide served as the dielectric medium (thickness, $d = 125$ μm, relative permittivity: $\varepsilon' \approx 3$). Sheets of copper (35 μm) were then glued and pressed onto both sides of the polyimide. This method allows for any two dimensional electrode configuration/shape to be manufactured. In this study, the copper electrodes were arranged in a linear, asymmetric fashion. The finished product is a sheet of flexible dielectric material with linear copper electrodes homogeneously attached. The dielectric material is flexible enough to wrap around the entire airfoil for these small-scale tests.

In order to research the ideal plasma location for a given parameter, electrodes were placed at the leading edge (LE) and quarter chord (QC), as well as 50% and 75% of the chord length. It was theorized that the ideal electrode placement for a given configuration is directly dependant on the location of separation its self. For example, if the flow becomes detached just aft of the leading edge, it is theorized that an electrode placed closely upstream will be the most effective location for flow control [4]. Throughout the experiments, relatively high angles of attack (8°, 12°, 16°) were explored. Therefore, only two electrode configurations were used for comparison; LE and QC.

Experimental protocol called for all electrode wiring to be contained within the airfoil such that nothing disturbed the flow field. Based on the scale of the wind tunnel test section, it was determined that the thickness of the NACA0024, relative to its chord length, would allow enough space to fit the required high voltage wires within the interior of the airfoil. Therefore, the NACA0024 was chosen as the airfoil to be used in testing. Additionally, The NACA0024 was chosen as an airfoil that readily induced flow detachment for the experimental parameters. The airfoil and its connecting components were designed using CAD software. The resulting files were then exported to 3D rapid prototyping machinery to produce physical models composed of an ABS plastic polymer. Due to the printing process, the surface of the airfoil was fairly coarse. In order to ensure a smooth lifting surface, the dielectric material was laid over the wing body as shown in Fig. 1.

Particle image velocimetry (PIV) was employed to quantify the behavior of the flow field during testing. The laser is a 25 mJ/pulse, double-pulse Nd-YAG laser (New Wave Research Co. Ltd., MiniLaser II, 20 Hz). A horizontal laser sheet would strike the airfoil at the midpoint of the wingspan. This produced a two dimensional cross-section of the flow field around the airfoil. Fig. 2 shows the experimental setup. Measuring from the mid-span location was done to minimize the effects of flow disturbances from the wing tips or test section walls. Atomized Dioctyl Sebacate (DOS) oil (diameter ≈ 1 μm) was injected upstream of the test section via a pressurized oil chamber. The YAG laser, which was synchronized with the TSI Inc., PIVCAM 13-8 camera, pulsed at 3.75 Hz. The PIV software can calculate the velocity vectors from the peak correlation of groups of particles in interrogation areas between frames, using conventional cross-correlation algorithms on a 32 × 32 pixel grid. By analyzing each vector field in succession, one is able to determine the flow field characteristics over a time scale.

Once the angle of attack, free stream velocity, and power supply settings are defined, the PIV system was turned on. Experiments were carried out such that the initial frames display the flow field without any manipulation by the DBD-PA. The plasma was then activated for approximately 2 s as to ensure a fully developed flow from the ionic wind. Instantaneous velocity fields convey little about the effect of plasma over time. Therefore, 20 samples at each fully developed instant were used to determine an averaged influence of the DBD-PA on the flow field. Comparisons were made between the plasma off/plasma on (pOFF/pON) conditions through these averages. The resulting data was used to develop an effectiveness chart for all of the varying conditions.

Electrodes from the dielectric sheet were wired to an external power supply (PSI Inc., PG1040F). Testing was performed at various frequencies and voltages to determine the ideal voltage and frequency case. Based on the results of this data, it was determined that the strength of the plasma is less dependant on varying voltage and frequency. Rather, the overall magnitude of the input power determines the velocity of the resulting ionic jet. Therefore, 8 $\text{kV}_{\text{p-p}}$

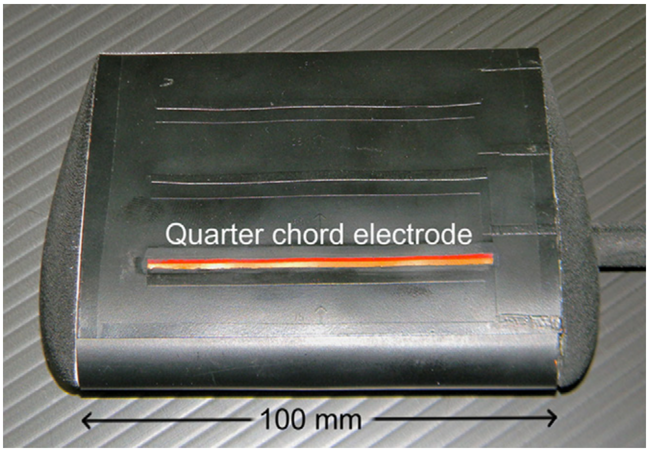

Fig. 1. NACA0024 with dielectric material stretched over the surface and QC electrode exposed.