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Original Research Article

Efficiency improvement study for small wind turbines through flow control

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ABSTRACT

In this study, a constant suction technique for controlling boundary layer separation at low Reynolds numbers was designed and tested. This was later implemented on small wind turbines. Small wind turbines need to operate in low wind speeds, that is, in low Reynolds number regimes – typically in the range 10^4—10^5. Airfoils are prone to boundary layer separation in these conditions, leading to a substantial drop in aerodynamic performance of the blades. Under these conditions turbines will have reduced energy output. This paper presents experimental results of applying surface-suction over the suction-surface of airfoils for controlling boundary layer separation. The Reynolds numbers for the experiments are kept in the range 8×10^4—5×10^5. The air over the surface of the airfoil is drawn into the airfoil through a slit. It is found that the lift coefficient of the airfoils increases and the drag reduces. Based on the improved airfoil characteristics, an analysis of increase in Coefficient of Power (C_P), versus input power for a small wind turbine blade with constant suction is presented.

1. Introduction

Small wind turbines can help provide energy to locations where other sources of energy are not available. In India, where currently more than 33% of the villages do not have access to electricity, off-grid community owned and operated small wind turbines can be a promising way of supplying electricity.

Usually, small wind turbines are installed close to the points of energy consumption. Such installation locations often see low wind speeds in comparison to those where large wind turbines are installed. Consequently, it is not uncommon that small wind turbines operate in regimes with chord-based Reynolds number as low as 5×10^4 [1]. At such Reynolds numbers, boundary layer separation is often seen in the presence of adverse pressure conditions. Such separation leads to a drastic drop in lift, increase in drag and thus poor aerodynamic performance. Such drop in aerodynamic performance is particularly severe at Reynolds numbers less than 10^5 (Fig. 1 [2]).

It is well-known that boundary layer separation may be delayed by applying active flow control techniques that include suction, use of pulsating jets, suction-blowing, air-jet vortices [3–7] amongst others. However, most such efforts aimed at realizing delayed boundary layer separation through flow control have focussed on higher Reynolds number applications. Efforts involving study of low Reynolds number applications have largely been directed only towards characterizing lift and drag data for a few airfoils. To date there appears to be a dearth of validated experimental data involving use of active flow control that may be used for designs pertaining to low Reynolds number applications including small wind turbines.

This work is aimed at addressing this dearth – specifically, aerodynamic characteristics pertaining to two airfoils, namely NACA0012 and S814 operating in low Reynolds number regimes, with suction control (Fig. 2) incorporated, is reported. Further, we make the argument that a horizontal axis small wind turbine constructed using one of these airfoils and incorporating suction control promises possible realization of Coefficients of Power (C_P) close to those typically seen in large ($\geqslant$ 500 kW) wind turbines. Section 2 describes the experimental set-up used to generate data pertaining to the aforementioned airfoils. Section 3 describe the

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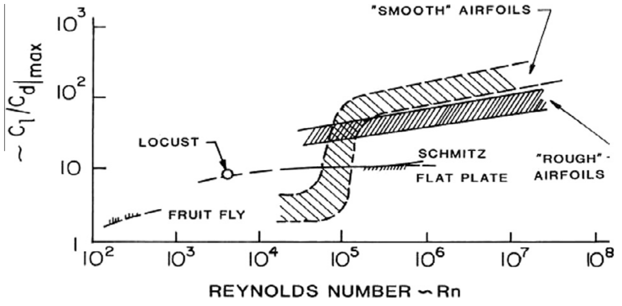

Fig. 1. Aerodynamic efficiency at various Reynolds numbers [2].

results pertaining to aerodynamic characteristics of these airfoils with and without suction control. Section 4 details the discussion of achieving C_P close to those seen in large wind turbines by using the results reported in Section 3.

2. Experimental set-up

In this section, we describe test specimens, wind tunnel details and test procedure pertaining to obtaining the aerodynamic characteristics, with and without suction control for two airfoils respectively with profiles, NACA0012 and S814. The symmetrical aerofoil profile, NACA0012 was chosen for its ease of construction and due to abundant availability of its data in literature to validate the results. A low-speed, wind turbine-specific aerofoil, S814 was chosen to obtain relevant data for wind turbines.

2.1. Test specimens

2.1.1. Airfoil profiles

For each of the airfoil profiles, a section with chord length of $c = 250$ mm and a span of $b = 200$ mm was fabricated. A 2 mm × 180 mm span-wise slit was created on the upper surface of the airfoils. A wide slit was chosen to avoid possible three dimensional flow effects. For the NACA0012 section, the suction slit was kept at a distance of x such that $x/c = 0.36$ from the leading edge whereas for the S814 airfoil section had the suction slit at the distance of x such that $x/c = 0.24$, from the leading edge.

Multiple slit positions were tested for both airfoils, from which the most effective positions were selected for each of the airfoils, based on the increase in C_L in the operating range of wind turbines, that is, angles of attack close to and slightly lesser than the stall angle. For NACA0012 airfoil, slit positions $x/c = 0.16, x/c = 0.36$ and $x/c = 0.56$ from the leading edge were tested. The slit closest to the leading edge ($x/c = 0.16$) provided maximum change in C_L at higher angles of attack and insignificant change in C_L at low angles of attack. The slit closest to the trailing edge provided maximum benefit at low angles of attack, and very less benefit close to the stall angle. The optimum benefit was seen for the centre slit, that is, when the slit was at $x/c = 0.36$ from the leading edge.

The slit positions tested for S814 were at $x/c = 0.12, x/c = 0.24$, $x/c = 0.44$ and $x/c = 0.64$ from the leading edge. The S814 profile has a thicker leading edge, which allowed the suction mechanism to be housed closer to the leading edge. The most beneficial slit position, by the same criterion as described above, was at $x/c = 0.24$. The reason why a smaller x/c ratio works better in the case of the S814 airfoil may be the fact that the S814 airfoil has a thicker root and a greater camber which in turn lead to a greater propensity for flow separation to occur at smaller x/c ratios, which can be better controlled by a slit position closer to the leading edge as compared to the NACA0012 airfoil.

Fig. 3(a) shows the NACA0012 airfoil profile with the suction slit at $x/c = 0.36$ and Fig. 3(b) shows the S814 airfoil profile with the suction slit at $x/c = 0.24$.

2.1.2. End plates

To maintain close to two dimensional flow over the airfoils and to avoid edge effects from the tips, the airfoil was mounted between two circular endplates with a diameter of $5c$ [8,9]. The airfoil was mounted at the "center" – consequently, the leading edge was at a distance of $2c$ downstream from the start of the end plates. The end-plates and the airfoil were held in place by a steel structure. All parts of the steel structure were downstream of the end plates and the airfoils such that the flow over the airfoil was not disturbed. The setup was mounted on a turn table which could be rotated with a resolution of 0.1°. The boundary layer thickness over the endplates was estimated using Blasius solution for the wind speeds that the specimen was to be subject to. The boundary layer thickness at the leading edge of the airfoil lies between 5.9 mm for wind speed 5 m/s and 2.4 mm for wind speed 30 m/s.

2.1.3. Suction

Suction was provided using a vacuum pump. The suction rate was varied using a valve. For each test, the rate of suction was kept constant for the period of averaging. The pump was connected to the airfoil from the two ends of the suction slit to provide a uniform flow in the slit. A venturi tube was used to measure the mass flow rate. The ratio of areas in the venturi was 2:1. The mass flow rate is:

$$Q = Area_1 \sqrt{\frac{2}{\rho} \cdot \frac{(p_1 - p_2)}{\left(\frac{Area_1}{Area_2}\right)^2 - 1}} \tag{1}$$

where $Area_1$ and $Area_2$ are the areas at the two measurement positions in the venturi tube, and p_1, p_2 are the pressures at the respective positions (Fig. 4). The average velocity of suction (u_s) at slit was calculated by dividing mass flow rate by the slit area. Momentum coefficient (c_μ) was used to quantify the rate of suction and is defined as the ratio of momentum of air drawn into the momentum of the air passing over the airfoil, i.e.

$$c_\mu = \frac{\rho A_{slit} u_s^2}{\rho A_{airfoil} U_\infty^2} \tag{2}$$

2.2. Instrumentation

2.2.1. Surface pressure measurement

Surface pressure was measured using pressure taps on the surface of the airfoil. Multiple pressure taps were placed on the

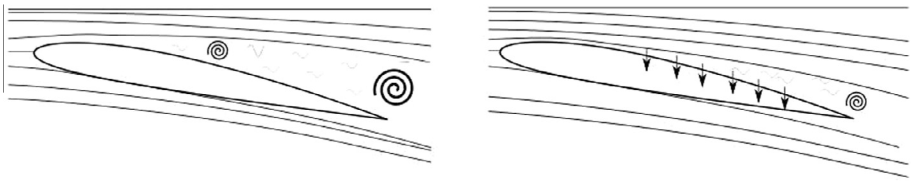

Fig. 2. Constant suction.