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Comparative study of NACA 4412 and NACA 4421 Profiles for Low Speed Wind Turbine Blade

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Abstract- *Renewable energy has received large attention in both developed and developing countries in the world as an alternative to the fossil fuel based energy. Wind energy is becoming one of the popular means to harness energy from renewable sources. Although abundant research had previously been undertaken for high wind speed turbines, research on wind turbine blades at low wind speeds is limited in the world. As such, in this paper a numerical study is performed for low speed wind turbine blades where two airfoils, namely NACA-4412 and NACA-4421 are chosen for comparative study. Numerical simulation was done via finite volume based software using a range of viscous models. The result shows that laminar, RNG k-ε and SST k-ω models are able to predict general behavior of both profiles, whereby laminar and SST k-ω models are able to capture stall angle. Whilst all the viscous models predicts well the pressure coefficient on lower side of the airfoil, but only laminar and RNG k-ε modesl perform better in the upper side of airfoil. The drag coefficient is found to be higher with the increase of AOA.*

Keywords: Airfoil, Numerical, Lift coefficient, Pressure, Drag

1. INTRODUCTION

Bangladesh has one of the fastest growing economies in the world. In this era of fourth industrial revolution, energy is the most vital element for industrialization. Bangladesh has already started investing in the power sector to achieve the goal of vision 2021. The country has a goal that the renewable energy generation capacity will be 10% of the total energy generation capacity of Bangladesh by 2021. According to the 'Power System Master Plan 2016', Bangladesh has a potential of generating 637 MW wind energy. But the progress in the field of wind energy is very limited due to the lack of sufficient wind or technological improvements in this area. The coastal area of Bangladesh is highly potential for wind energy generation, but relatively low average wind speed (5 m/s or even low) hinders the expansion of wind farms. The wind speed is even less in the inland (about 3.5 m/s) regions. This low-speed, indeed, is very close to the cut-in speed (when the speed is sufficient to overcome inertia) of a wind turbine. This is also one of the reasons for relatively low generation of wind power and not a popular means of power generation. As such, there is a strong need to conduct a fundamental research on how to improve a wind turbine blade so that it can be applied at relatively lower wind speed. The consequence is a wind turbine may be deployed at both inland and coastal area of Bangladesh, unlike presently only at the particular places of coastal area. This investigation may positively impact on the future demand of energy in Bangladesh.

Plenty of research works have been done to analyze the fundamental characteristics and performance improvement of high speed wind turbine blades, as this type of blades have been implemented throughout the world. In contrast, research on small and low speed wind turbine is comparatively limited in the literature. An extended research on small wind turbines as well as development issues have been presented [1-2]. The modified type of wind concentrator has been proposed and studied for the improvement of system output by Bechly et al [3]. The starting behavior of a small horizontal-axis wind turbine is a very important issue which may have a great impact on its performance and has been thoroughly examined by Ale et al. [4]. The Savonius and Darrieus wind turbine types are the most usual VAWT system, a combination of these two types has also been suggested by Wakui et al. [5]. Ale et al [4] investigated airfoil drag and tip losses that are a function of the total number of blades reduce the power coefficients of wind turbines. Singh and Ahmed [6] and Koutroulis and Kalaitzakis [7] showed that, in comparison with the baseline 3-bladed rotor, the new 2-bladed rotor produced more electrical power at the same freestream velocity. Masters et al. [8] have shown a robust blade element momentum theory model for turbines including tip and hub loss corrections by using combined Monte Carlo and sequential quadratic optimization. Recently, Tasnim et al. [9] conducted fluid-structure interaction of a low twist angle wind turbine blade. They found that deflections are mainly observed near the tip, but critical stress developed near the root. A linear power curve against torque is also developed from velocities. Genetic algorithm is now very popular for optimization, and has been applied in many applications [10]. Ribeiro et al. [11] use genetic algorithm (GA) and artificial neural network (ANN) along with computational fluid dynamics to optimize an airfoil. They showed that genetic algorithm saves almost 50% computational time. Shahrokhi and Jahangirian [12] also did similar work using genetic algorithm to parameterize airfoil shape for optimum Navier-Stokes design. Also in Bangladesh, several research works and government initiative was taken. SREDA has been working on a wind resource mapping project to identify the potential area for future wind energy harvesting. Also another similar work of wind mapping was done by Khan et al. [13].

It appears that very little works have been undertaken on low speed wind turbine blades. Even, there is no complete study on airfoils at low speed wind turbines. As a result, there is a strong need to investigate fundamental studies on low speed wind turbine blades, particularly in Bangladesh in order to meet local renewable energy demand. In this study, a comparative study of two NACA airfoils is performed numerically to start with. The lift, drag and other flow parameters are compared with experimental data to validate the methodology for future fundamental analysis.

2. METHODOLOGY

The governing equations for the current problem are continuity equation and momentum equations. Momentum equations include both laminar and turbulent conditions, whereby turbulent flow governing equations are considered as RANS equations. For the numerical simulation, a commercial software package ANSYS Fluent v16 was used to solve the governing equations. The methodology consists of profile selection for low wind speeds, mesh generations, boundary conditions and viscous models choosing.

2.1 Profile Selection

There are number of airfoils, which are believed to be effective and suitable for low wind speed cases, available in the literature. Examples of these airfoils are

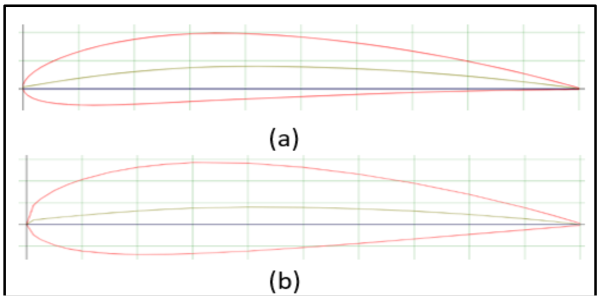

Fig.1: Geometry of investigated airfoil profiles: (a) NACA 4412 and (b) NACA 4421

NACA 4412, NACA 4418, NACA 4421, NACA 63412 and NACA 63415. Among these variations, only NACA 4412 and NACA 4421 are considered in this study due to their availability of detailed experimental data. The geometry of the selected profiles is shown in Fig. 1.

2.2 Mesh Generation

The numerical domain is a C-mesh, consists of a flow field, inlet, outlet and the airfoil body. Structured mesh is used for faster iteration. Quadrilateral mesh element is chosen here. The density of mesh is higher near the surface of the airfoil to capture near-surface flow physics. A total of around 90,000 mesh element is used, after the mesh independency test.

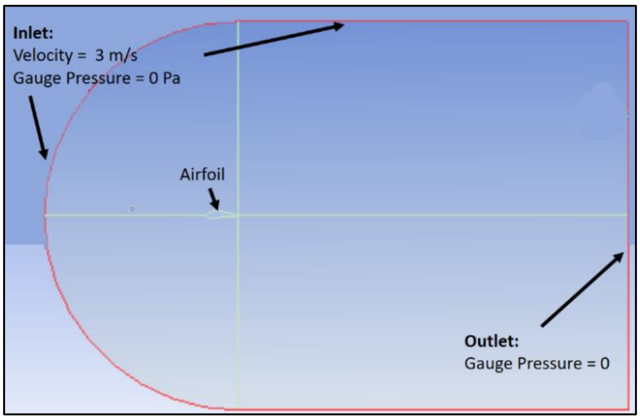

Fig. 2: Numerical domain

A second-order upwind discretization technique and pressure based coupled solver is used. Atmospheric air is used as fluid medium, with density (ρ) 1.225 kg/m^3 and viscosity (μ) 1.789x10^{-5} kg/(ms). Velocity inlet is chosen in the domain inlet with uniform wind velocity of 3 m/s. The corresponding Reynolds number (Re) and Mach number is 20,000 and 0.0087, respectively. Atmospheric pressure is considered at the pressure outlets. No slip boundary condition is applied at the airfoil surface. The convergence is assumed to achieve when the residuals of the variables reaches to 10^{-5}.

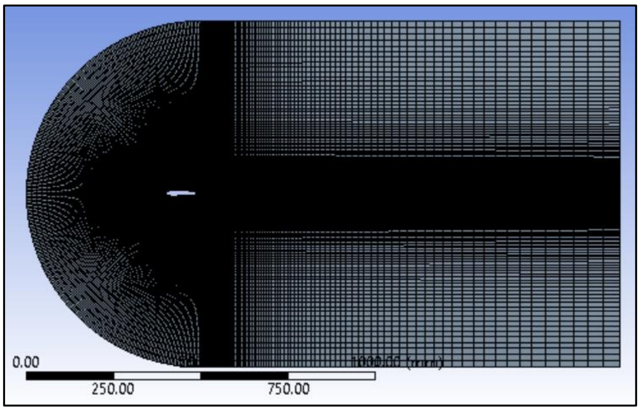

Fig.3: C mesh generation

2.3 Viscous Models

Different viscous models are available in standard ANSYS Fluent suit for numerical simulations. However, following models are used in this study, and they are chosen based on their superiority in wall bounded flows.

The models are:

i. Laminar
ii. Transition SST model
iii. K-ω SST model
iv. RNG k-ε model
v. Transition k-kl-ω model

3. RESULTS & DISCUSSION

In this section, both lift and pressure coefficients of the selected profiles are presented first, and are validated against published benchmark data. The drag coefficients of both profiles are discussed then.

Fig. 4 shows the lift coefficients for both profiles (NACA 4412 (Fig. 4a) and NACA 4421 (Fig. 4b)) against the angle of attack in the range 0º-18º for low wind velocity. In this regard, five different viscous models are compared with two experimental data [14, 15]. Figure 4a shows that laminar and SST k-ω model perform better than others at lower Reynolds number (Re = 1.5×10^6). Although laminar model agrees well with the experimental data up to the stall angle, but after the stall the laminar model cannot predict the sharp downward tendency of C_L. On the other hand, RNG k-ε model outperforms other models at larger Reynolds number (Re = 3×10^6), even after the stall. The model k-kl-ω does not predict the experimental data in the neighborhood of stall. In contrast, for NACA 4421 case (Fig. 4b), all the models predicts general behavior well, except k-kl-ω, which does not agree completely in terms of characteristics and magnitude with the experimental data.

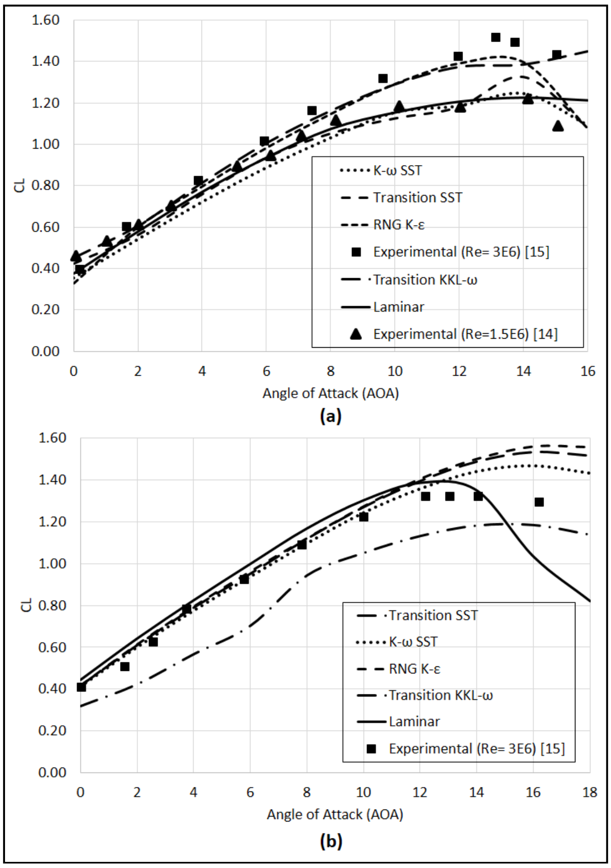

Fig. 4: (a) Coefficient of lift (C_L) against angle of attack (AOA) for (a) NACA 4412, and (b) NACA 4421 airfoil.

While all the turbulence models agree the experimental C_L characteristics before and after the stall, but only laminar model predicts the stall angle accurately. However, similar to the NACA 4412 case, laminar model is not able to capture C_L after the stall angle, and large deviation is observed. It appears that stall angle is almost the same for both profiles (about 14º), as observed from experimental results regardless of Reynolds number. For numerical results, RNG k-ε and laminar models is able to predict stall angle accurately with the expense of little discrepancy in magnitude for NACA 4412 and NACA 4421, respectively. If one has to choose one or two models for both profiles considering stall angle, overall behavior and magnitudes, that would be SST k-ω or laminar model. Other viscous models are good for angles less than the stall angle i.e. ≤12º.

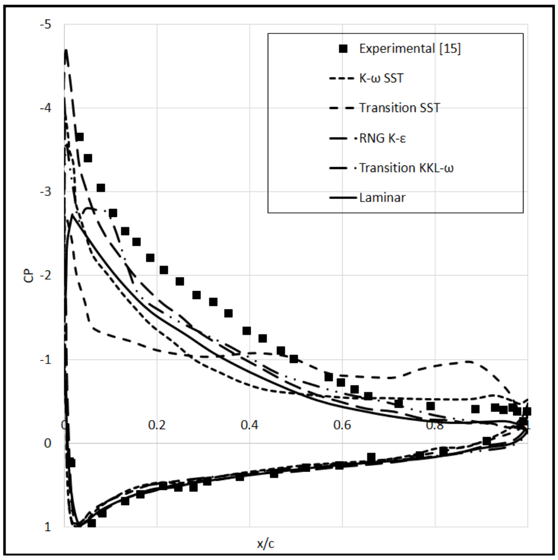

Fig. 5: C_P distribution of airfoil NACA 4412 at 14ºAOA

Fig. 5 depicts the Cp distribution of NACA 4412 airfoil at stall angle i.e. 14º. It is clear from the figure that the numerical results predicts the experimental data accurately the lower side of the airfoil (positive magnitude portion of the plot), irrespective of the models. A slight variation in the rear side of the airfoil is observed, but not substantial. In contrast, a significant and strong deviations are observed among the models when compares with experimental data in the upper side of the airfoil. Though a reduced Cp is predicted numerically for all models, laminar, RNG k-ε and SST k-ω models perform better. The discrepancy between experimental and numerical result at the upper side of the airfoil may be due to the large variations of Reynold number. In the simulation Reynolds number equal to 20,000 is considered whereas experimental data is at Re=3×10^6. It is worth noting detailed data for low wind speed (hence low Reynolds number) airfoil is limited in the literature. Thus, the negative pressure generated on the upper side of the airfoil is capable enough to produce lift but the magnitude is comparatively lower than the pressure generated for higher Reynolds numbers.

Finally, Fig. 6 shows the change of drag coefficient along with AOA. Higher drag force can be obtained by increasing the AOA. This increase is found to be steeper in NACA 4421 than NACA 4412. A strong deviation is observed among the models near or after the stall angle for both airfoils. Both lift-driven and drag-driven blades are used for wind turbines. The airfoil has to be chosen for designing the blade based on the objective and constrains of wind turbine.

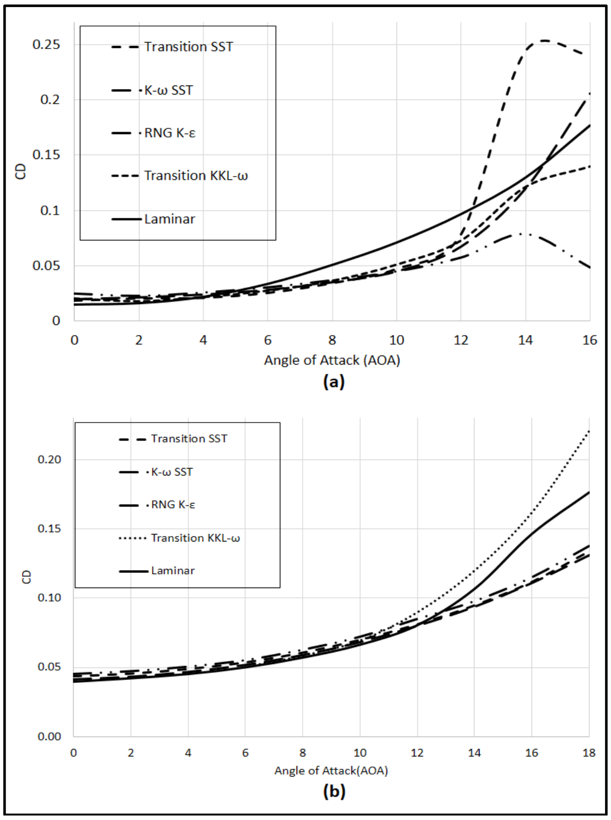

Fig. 6: (a) Coefficient of drag (C_D) against angle of attack (AOA) for (a) NACA 4412 and (b) NACA 4421

The current paper is the part of a larger project which focuses low Reynolds number case, and it aims to understand better how data at high wind velocity correlates with the data at low wind velocity. Additionally, this paper shows a step towards validation of existing viscous models in CFD with predominantly turbulent experimental data. The low speed wind turbine may well be predicted at laminar models that would essentially require less number of equations; thereby reducing computation cost.

4. CONCLUSION

In this paper, a numerical study is conducted for two airfoils (NACA 4412 and NACA4421) pertaining to the low wind speeds turbine blade. Numerical simulation was performed via ANSYS Fluent v16 using five viscous models. The results show that despite three viscous models, namely, laminar, RNG k-ε and SST k-ω models predict general characteristics of both profiles, laminar and SST k-ω models are able to capture stall angle. Whilst all the viscous models predicts well the pressure coefficient on lower side of the airfoil, but only laminar and RNG k- ε model perform better in the upper side of airfoil. The drag coefficient is found to be higher with the increase of AOA.

5. ACKOWLEDGEMENT

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NOMENCLATURE

Symbol	Meaning	Unit
Re	Reynolds Number	Non -dimensional
P	Pressure	(Pa)
T	Temperature	(K)
μ	Viscosity	Kg/ m-s
U_∞	Free stream velocity	m/s
ρ	Density	Kg/m^3