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AIRFOIL SELECTION FOR AERODYNAMIC PERFORMANCE CRITERION ON SMALL WIND TURBINES

Emanuela Sorina SOUCA, Cornel CIUPAN

Abstract: *Performance optimization is one of the major concerns in wind turbines industry and especially for small wind turbines, which are mostly found in the urban areas. As we know, urban areas have a turbulent wind flow, frequent changes of wind flow direction and intensity, gusts and other obstacles. This paper focuses on studying the aerodynamic performance of different airfoils which are widely used on small wind turbines. The results obtained from airfoil analysis have shown that asymmetric profiles are suitable for small wind turbines, because they have the best aerodynamic lift drag ratio on a big range of attack angles.*
Key words: *small wind turbines, airfoil profile, aerodynamic performance, drag, lift.*

1. INTRODUCTION

The aerodynamic profile of the blade represents the blade section or its geometric outline obtained by sectioning it with a horizontal plane in case of vertical wind turbines - VAWT, or a vertical plane in case of horizontal wind turbines - HAWT or aircraft wings. The airfoil aerodynamic profile is an essential component when building wind turbines, with major influences on their performance and aerodynamics.

Thus, to choose a blade profile, it is necessary to have solid knowledge and studies to avoid any negative effects caused by the incorrect choice of a profile. To facilitate the choice of profiles we can appeal to organizations' catalogs. The most popular classes of airfoil sections are: Joukowski, Eppler (E168, E178), Profiles Wortmann (FX60-126-1-137 FX63, FX77-W-153, FX77-W-258), NACA, Class N (N60 , N60R), RAE, Gottingen (GOE358, GOE176, GOE496), NLR, NASA, SANDIA, but also the profiles of small wind turbines manufacturers such as Berghey WindPower (SH3052, SH3055, BW-3), NREL (S1210, S822, S834) and many more [1] [2].

NACA family (National Advisory Committee for Aeronautics) is the most famous family of airfoils with many applications in wind turbines, particularly in numerical validations. NACA was also the predecessor of NASA, and it is studying different families of profiles corresponding to various applications. The most famous families are NACA four-digit family and NACA five-digit.

NACA four-digit aerodynamic profile families are characterized by four numbers, the first representing the maximum camber of the chord as a percentage, the second digit indicates the position of maximum camber and the last two represent the maximum thickness of the profile.

Airfoil shapes can be found on wings, fans and propellers. The airfoil shape provides a lifting force when air flows around it. An airfoil has a thicker rounded leading edge (front end) and a very thin trailing edge (or back end). In between the leading and trailing edge it is curved both on the top and on the bottom surfaces. The top surface usually has a greater curve (or hump) than the bottom surface. When a surface is curved we say it has camber [3;4].

According to Bernoulli's principle, the air flows faster over the top of the wing than it does underneath. The top surface of the wing has more camber than the bottom surface. This means that there is less air pressure above the wing than there is beneath the wing. The difference in air pressure above and below the wing causes lift.

2. FORCES ON AN AERODYNAMIC PROFILE

All objects exposed to an air flow are characterized by the appearance of the aerodynamic forces, the drag force with same direction as the air flow, and the aerodynamic lift force perpendicular to the flow direction (figure 1). For most types of wind turbines, the lift is responsible for blade rotating, in a perpendicular plane to flow direction. Aerodynamic profiles are optimized to develop a higher lift and a low drag.

Lift is the aerodynamic phenomenon whereby a body is floating or is held in the air due to its movement. Examples of lift bodies are airplane wings, aircraft propeller blades or fan and wind turbine blades.

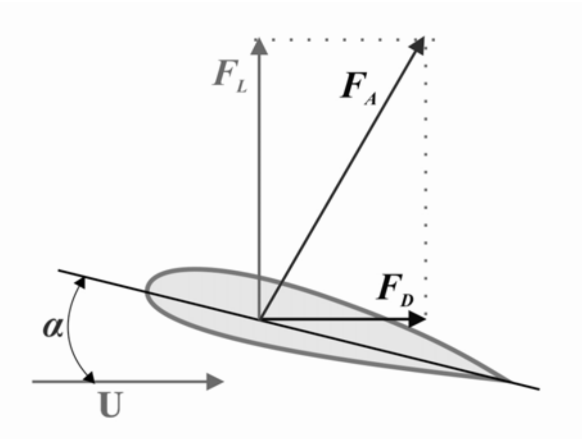

Fig. 1. Forces on an aerodynamic profile.

The appearance of aerodynamic forces is strongly influenced by the attack angle α between the blade and the flow direction. Thus, a null angle on the top and bottom of the wing will result in depressions which will cancel each other therefore the lift force is zero and on the profile will act only the drag force. Small and normal positive angles will create depressions on the upper side and pressures on the lower side, which summed will give the lift force that is growing with increasing depressions on the upper side.

3. AERODYNAMIC PROFILE POLARS

Most of the market research on aerodynamic profiles is applicable to aviation and airline industry or in large capacity wind turbines which correspond to high Reynolds numbers (> 1000000 Re). Small capacity wind turbines are characterized by low Reynolds numbers in the range 100000-500000 and knowledge of their behavior becomes a necessity [1].

Blade profiles, for small-capacity turbines which operate at low wind speeds are characterized by a quasi-linear behavior at low Reynolds numbers.

In order to assess the performance of an airfoil it is necessary to know the drag coefficient C_D, the lift coefficient C_L and the moment coefficient C_m. These are defined based on the following relations:

$$C_D = \frac{F_D}{\frac{1}{2}\rho U_{rel}^2 A_p} \quad (1)$$

$$C_L = \frac{F_L}{\frac{1}{2}\rho U_{rel}^2 A_p} \quad (2)$$

where ρ is air density, U_{rel} air flow relative velocity, A_p profile area, F_L lift force, F_D drag force.

Profile polars can be drawn based on the aerodynamic coefficients in relation with the angle of attack, between relative velocity and chord. The dependence of the lift and drag coefficient depending on the angle of attack is called lift to drag ratio.

As stated previously, aerodynamic profiles behave differently at certain values of Reynolds number based on the air flow velocity, so it is very important to choose the profile according to expected speed range and to plot their polar curves for different Reynolds values [5;8].

To calculate the Reynolds number for different profiles it is necessary to know the characteristic length and characteristic velocity. The relation for Reynolds number is:

$$\mathrm{Re} = \frac{\rho U l}{\mu} = \frac{U}{\nu} \approx 71 U l \quad (3)$$

where ν is kinematic viscosity coefficient, *U* specific velocity and *l* characteristic length (for blade profiles it is equal to the length of chord).

Depending on the Reynolds number, airflow movement can be laminar or turbulent.

Profile polars are usually obtained from the investigations in wind tunnels and numerical calculations. This kind of research takes time and material resources, often the results being influenced by many factors. The evolution of computer technology has resulted in programs that allow polar calculation for different profiles with high accuracy compared to experimental results.

The most popular computer programs for profile polars are: XFOIL Code (developed by Mark Drela), Eppler Airfoil Design and Analysis Code (PROFIL00), Profili 2 (developed by Stefano Duranti), DesignFOIL (DreeseCode Software Company) etc. [1]. Programs have a large airfoils database and allow changing geometries and comparing polars for different blade profiles in relation to various factors.

4. BLADE PROFILE SELECTION

In order to achieve the wind turbines proposed in this thesis NACA family profiles were chosen, that is both the symmetrical profiles NACA 0018 and 0015, as well as the asymmetric profile NACA 4418. The drawing of the polars and their analysis for this type of blade profiles was done in Profili v2.30a software, a program that holds a data base of 2217 profiles and has a wide range of facilities. In this case, the program was used for drawing the polars of the chosen profiles depending on the angle of attack for different Reynolds numbers, comparing a group of profiles and analyzing the pressure distribution for each profile.

The chosen field for the analyzed Reynolds numbers is between 80000 and 500000, because as stated before, small capacity wind turbines operate at lower wind values.

The selected profiles are characterized by high values of aerodynamic fineness (the ration between the lift coefficient C_L and the drag coefficient C_D) in a wide range of the angle of attack α, for low values of the Re number (such as the Re numbers at which small capacity wind turbines operate).

The number Re=80000 corresponds to a speed of about 5 m/s, a value from which most turbines begin to produce energy; for Re=100000 the speed is between 7 and 8 m/s; for Re=170000 the speed is between 12 and 13 m/s, a value close to the nominal value of small capacity wind turbines; 22 m/s for Re=300000; and 37 m/s for Re=500000, a value close to the cut-out speed (COS) of wind turbines.

From blade profile point of view we have different types of blades, concave-convex profile, plane convex profile, symmetrical biconvex profile and asymmetrical biconvex profile. Studies showed that for vertical axis wind turbines, NACA profiles are most frequently used. The most common profiles are symmetrical profiles NACA 0018, 0015 and 0012. These profiles are turbulent, the laminar boundary layer as seen in the leading edge has a small length, which minimizes the risk of formation of separation bubbles. This is explained by the rapid transition of the boundary layer from laminar to the turbulent state with the consequent increase of the friction forces on the profile [6; 7].

4.1. NACA 0015 Profile

The nature of the curves' behavior of these dependencies following the analysis allows us to appreciate the performance of the NACA 0015 profile (Figure 2 and 3) for the lower limit of Re=80000 reaching a relative lift to drag ratio of about C_L/C_D = 33.41 at a value of the angle of attack $\alpha = 6^o$. This behavior has a constant evolution regarding the profile's performance, which increases to Re = $0.5*10^6$, reaching a lift to drag ration C_L/C_D = 66.55 at a value of the angle of attack $\alpha = 7.5^o$.

The maximum values of the profile fineness and the corresponding angle of attack for the other Re numbers are shown in Table 1; the pressure distribution on the profile at a wind speed of 12-13 m/s, and the angle of attack for which the lift to drag ratio C_L/C_D is maximum corresponding to a Re number of about 170000 is represented in Figure 4.

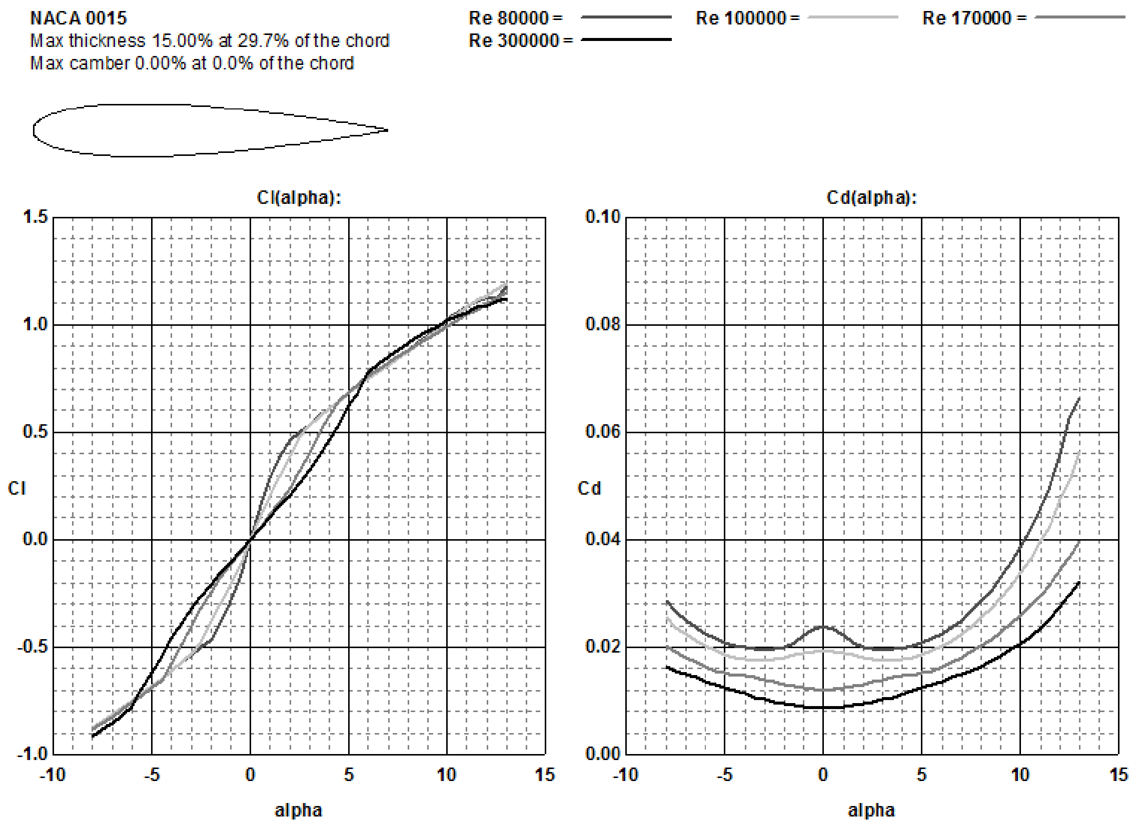

Fig. 2. The performance of NACA 0015 profile for different Reynolds numbers, $C_L(\alpha)$ and $C_D(\alpha)$. (Profili v2.30a)

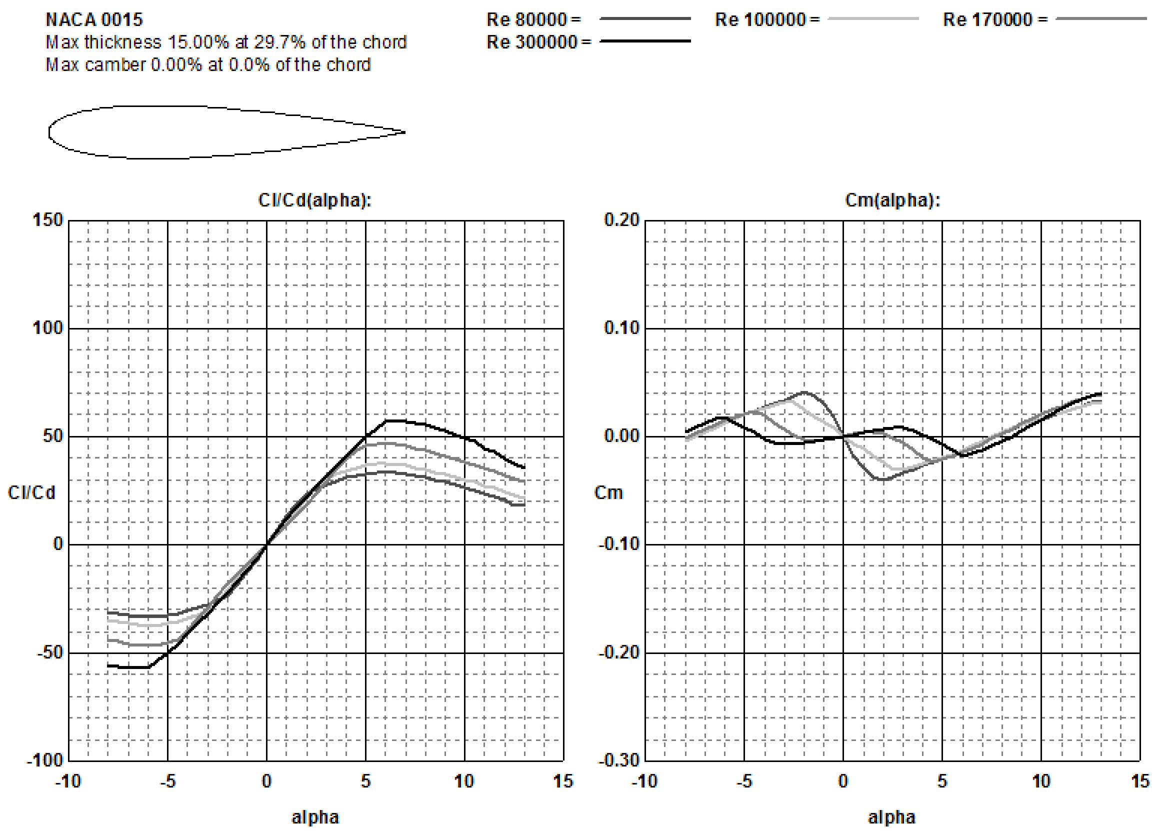

Fig. 3. The performance of NACA 0015 profile for different Reynolds numbers, C_L/ C_D (α) and $C_m(\alpha)$. (Profili v2.30a)

Table 1

Lift to drag ration of NACA0015 profile in relation to the angle of attack.

	Reynolds number Re	Angle of attack α	Lift to drag ratio Cl/Cd
NACA 0015	80 000	6^o	33.41
	100 000	5.5^o	37.23
	170 000	6^o	46.69
	300 000	6.5^o	57.20
	500 000	7.5^o	66.55

Table 2

Lift to drag ratio of NACA 0018 profile in relation with the angle of attack.

	Reynolds number Re	Angle of attack α	Lift to drag ratio Cl/Cd
NACA 0018	80 000	7^o	33.16
	100 000	6.5^o	37.26
	170 000	7^o	46.85
	300 000	8^o	57.40
	500 000	9^o	65.76

4.2. NACA0018 Profile

NACA 0018 profile differs slightly from the one examined above, having a quasi-linear behavior and a maximum lift to drag ration for the upper limit of the number Re equal to C_L/C_D =65.75 for $\alpha = 9^o$ (Figure 6 and 7).

The pressure distribution on the profile at a wind speed of 12-13 m/s, and the angle of attack for which the lift to drag ratio C_L/C_D is maximum corresponding to a Re number of about 170000 is represented in Figure 8.

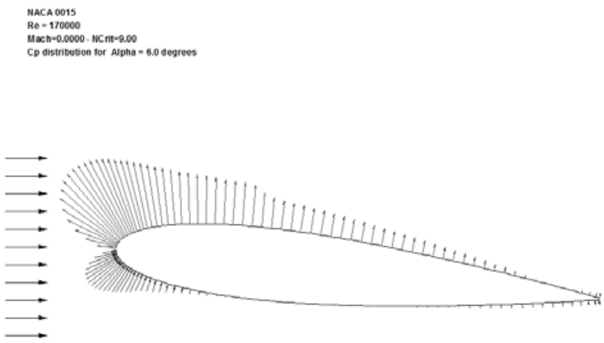

Fig. 4. Pressure distribution on NACA 0015 profile for the optimal angle of attack α. (Profili v2.30a)

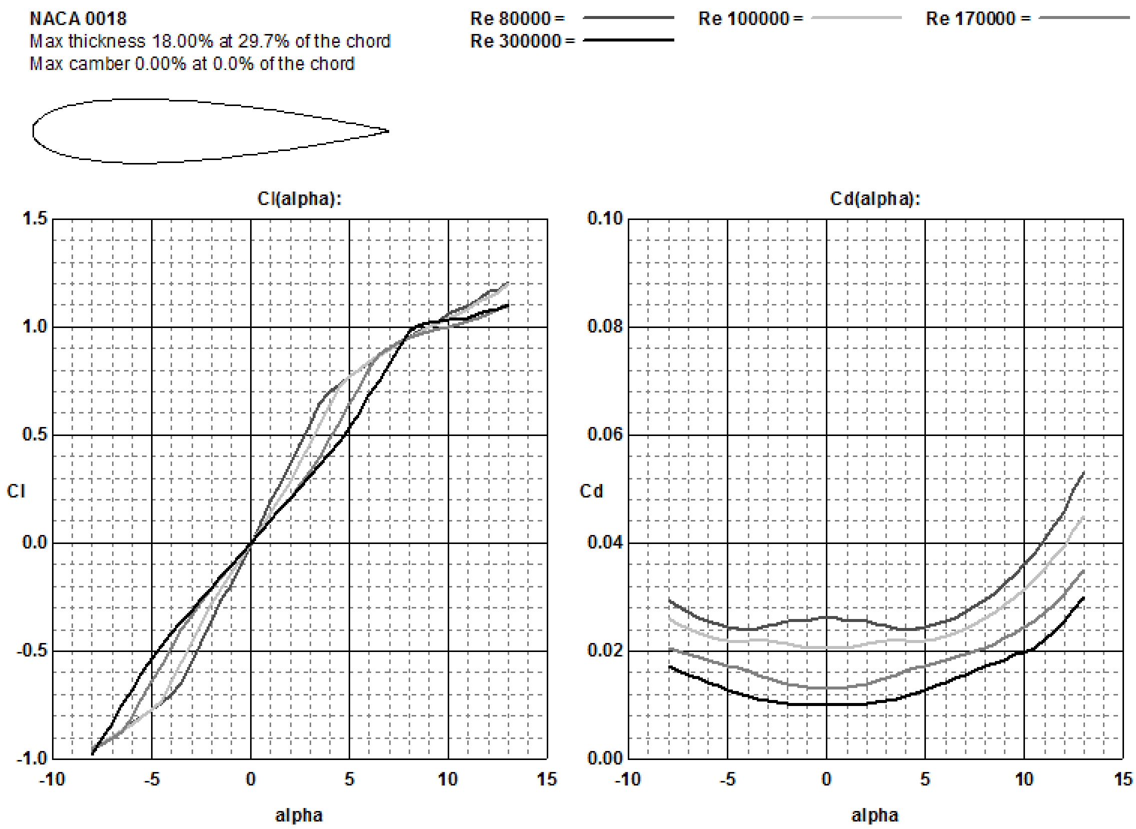

Fig. 5. The performance of NACA 0018 profile for different Reynolds numbers, $C_L(\alpha)$ and $C_D(\alpha)$. (Profili v2.30a)

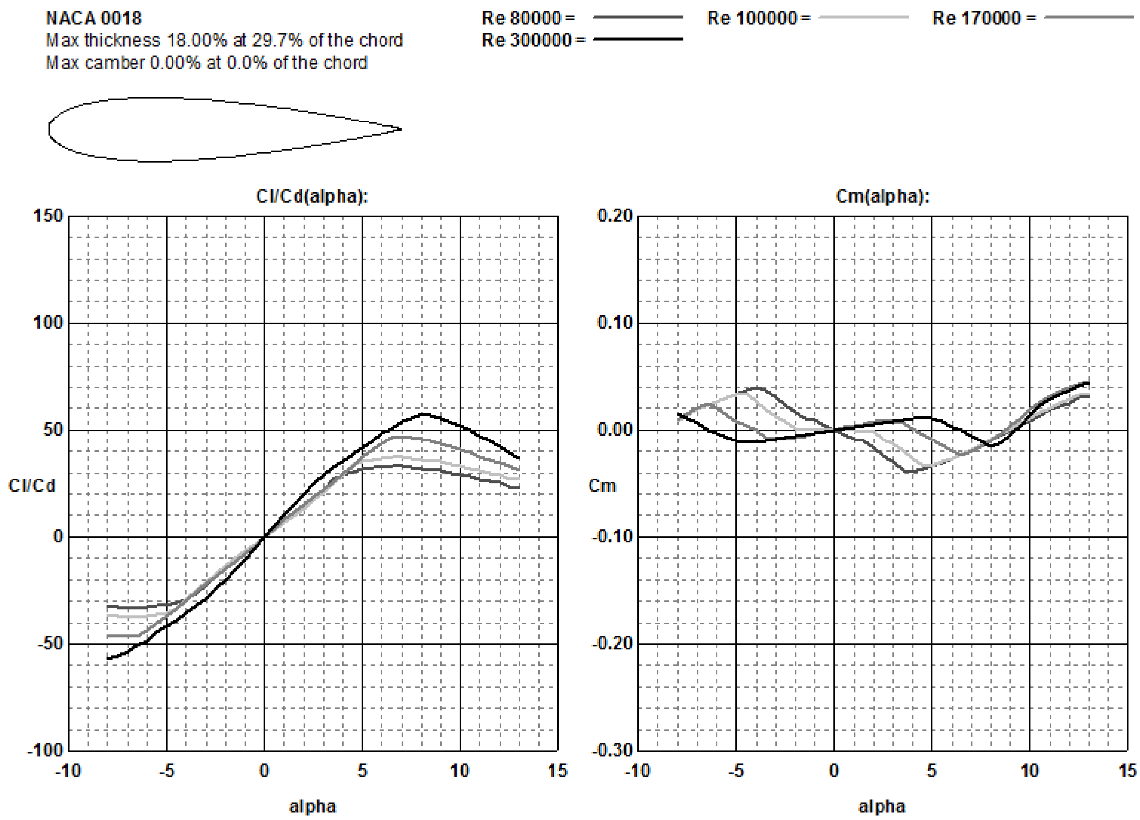

Fig. 6. The performance of NACA 0018 profile for different Reynolds numbers, C_L/C_D (α) and C_m(α). (Profili v2.30a)

4.3. NACA 4418 Profile

In the case of NACA 4418 profile (Figures 10-11), for the upper limit of the Reynolds number (Re=500000) there is a drop in performance compared to the lower limit of the number Re. This drop, in combination with the increased resistance of the profile is probably due to the separation of the air bubbles from the laminar layer, which then no longer integrate on most of original flow lines. For the upper limit of the Re number the profile reaches a maximum lift to drag ratio of C_L/C_D = 55.31 for the angle of attack α = 2°.

Table 3

Lift to drag ratio of NACA0018 profile in relation to the angle of attack.

	Reynolds number Re	Angle of attack α	Lift to drag ratio Cl/Cd
NACA 0018	80 000	8°	40.91
	100 000	7.5°	47.50
	170 000	5.5°	58.31
	300 000	3.5°	62.77
	500 000	2°	55.31

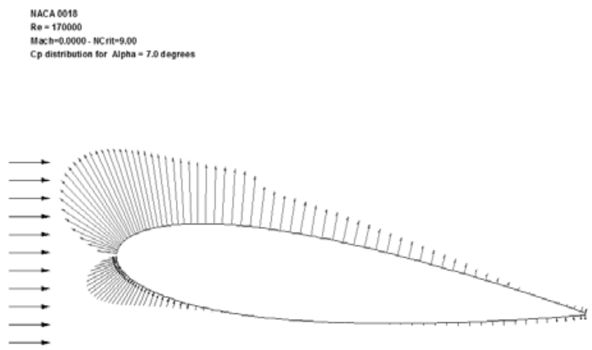

Fig. 7. Pressure distribution on NACA 0018 profile for the optimal angle of attack α. (Profili v2.30a)

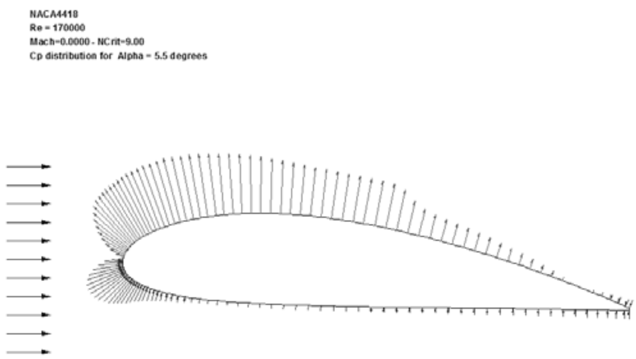

Fig. 8. The pressure distribution on NACA4418 profile for the optimal angle of attack α. (Profili v2.30a)

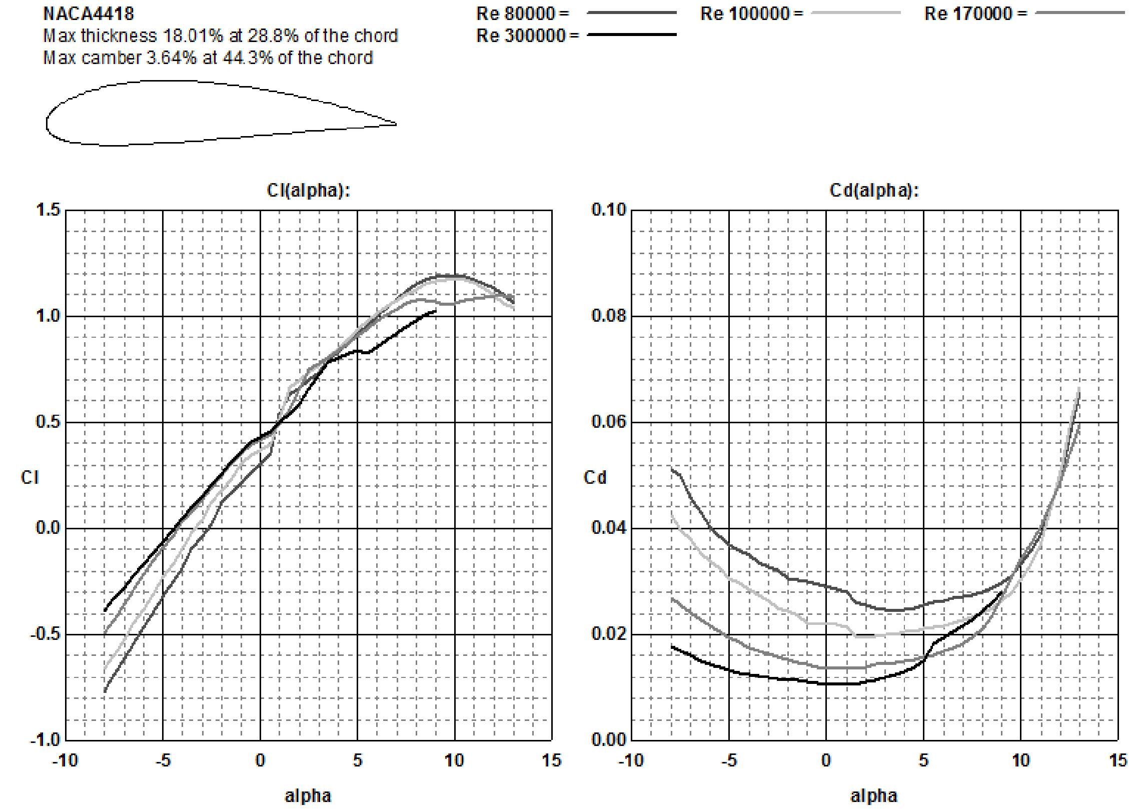

Fig. 9. The performance of NACA 4418 profile for different Reynolds numbers, $C_L(\alpha)$ and $C_D(\alpha)$. (Profili v2.30a)

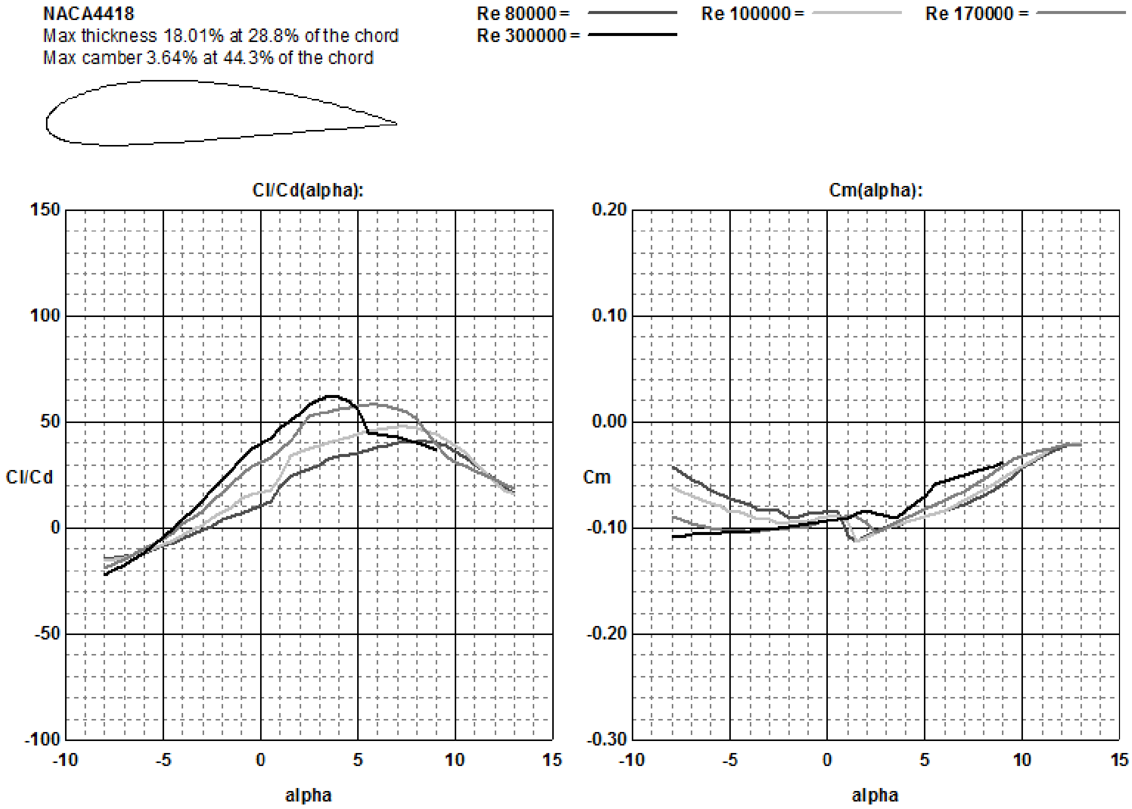

Fig. 10. The performance of NACA 4418 profile for different Reynolds numbers, $C_L/C_D(\alpha)$ and $C_m(\alpha)$. (Profili v2.30a)

4.4. Comparison of the studied profiles

The NACA 4418 profile has the best performance for which the lift to drag ratio C_L/C_D of the profile is higher on almost the entire area, thus justifying its election as a reference model for the rest of the simulations (Figures 12- 13).

5. CONCLUSIONS

Growing awareness of the effects caused by fossil fuels, global warming, and accelerated reducing of conventional energy resources with the increase in price has led to the development of small capacity turbines.

Simple structure, compact design, low noise, compactness, etc.. for small capacity wind turbines, are vital for the production of electric power in rural areas or in cities where it is not possible to install high capacity turbines, because of space and noise.

Large capacity wind turbines are placed in optimal conditions to extract sufficient wind energy, while the low-capacity wind turbines have to produce energy not always in favorable conditions.

Due to the conditions required by the building, vertical axis wind turbines have a number of advantages compared with horizontal axis, but on the other hand due to the reduced know-how and information relating to the performance of the VAWT turbines, the accurate modelling of the aerodynamics poses a significant challenge.

The cyclic motion of the turbine induces large variations in angle of attack for blades, thus variations of blade aerodynamic loading. The interaction of turbine blades and the vortices generated by previous revolutions produce variations in blades aerodynamic and are difficult to simulate accurately. The VAWT turbine characteristics are more complex compared to HAWT, which currently is in an advanced stage of knowledge. VAWT turbines because of that and because the fact that the developments have focused more on HAWT turbines, have many unknown and are difficult to understand in terms of aerodynamic behavior [9, 10].

The shape of a blade's profile is a fundamental feature affecting the aerodynamic characteristics and performance of a wind turbine. The compromise between performance and mechanical strength is at the core of the definition and optimization process regarding the geometry of the blade.

Analyzing the behavior of the aerodynamic coefficients in relation to the angle of attack, one may conclude the following:

- The more the camber increases, the C_L, C_D, C_m coefficients will increase as well, and the angle of attack will decrease;
- The drag coefficient C_D increases with the relative thickness, the lift coefficient C_L is maximum for profiles with relatively medium thickness, and the critical angle of attack increases slightly;
- The lift coefficient C_L increases in relation to number Re; an increase of Re will increase also the maximum C_L and the critical α.

Small capacity wind turbines are operating at low Reynolds numbers, so their aerodynamic behavior is strongly influenced and the changing angle of attack is an essential element in the construction and development of wind turbines.

Power coefficient variation caused by continuous change of the blade angle of attack with turbine rotation constitutes the biggest challenge in the construction of vertical axis wind turbines. Thus, researches in this field are aimed at finding solutions to decrease this invariableness performance.

6. ACKNOWLEDGEMENTS

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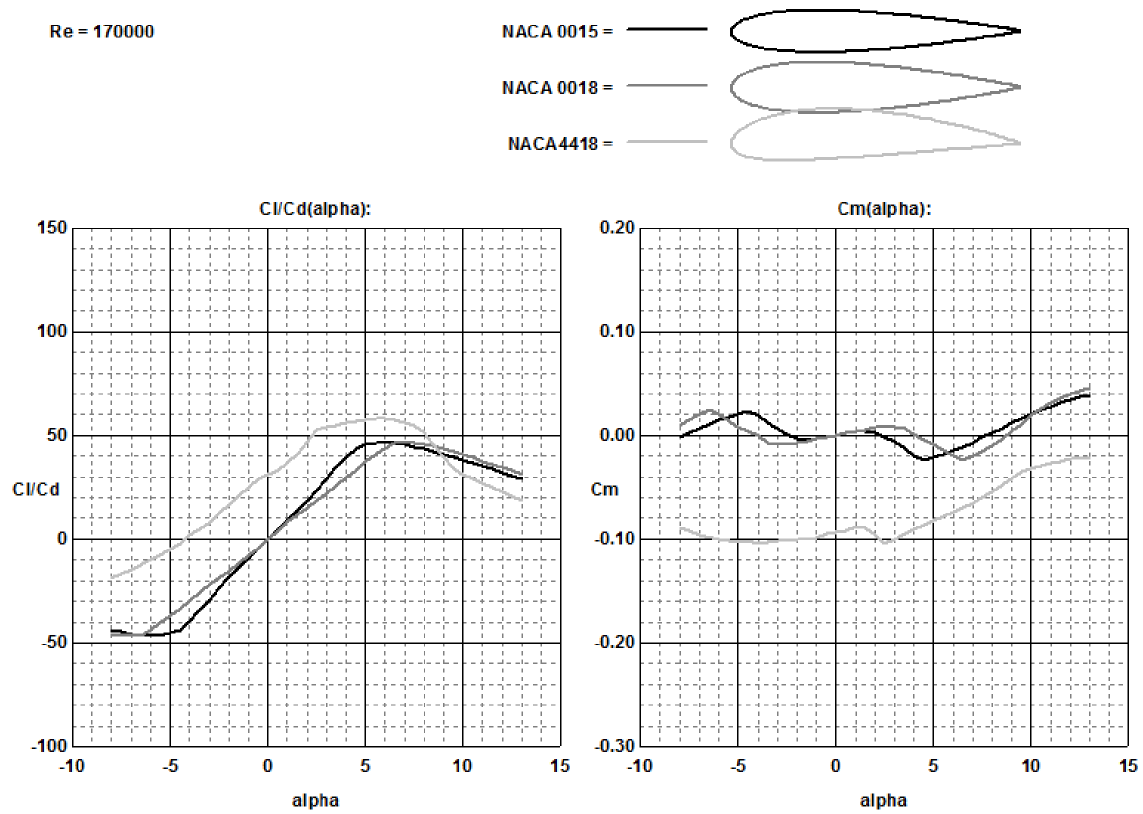

Fig. 11. Comparison of aerodynamic coefficients for NACA 0015, NACA 0018 and NACA 4418 profiles for number Re = 170000. (Profili v2.30a)

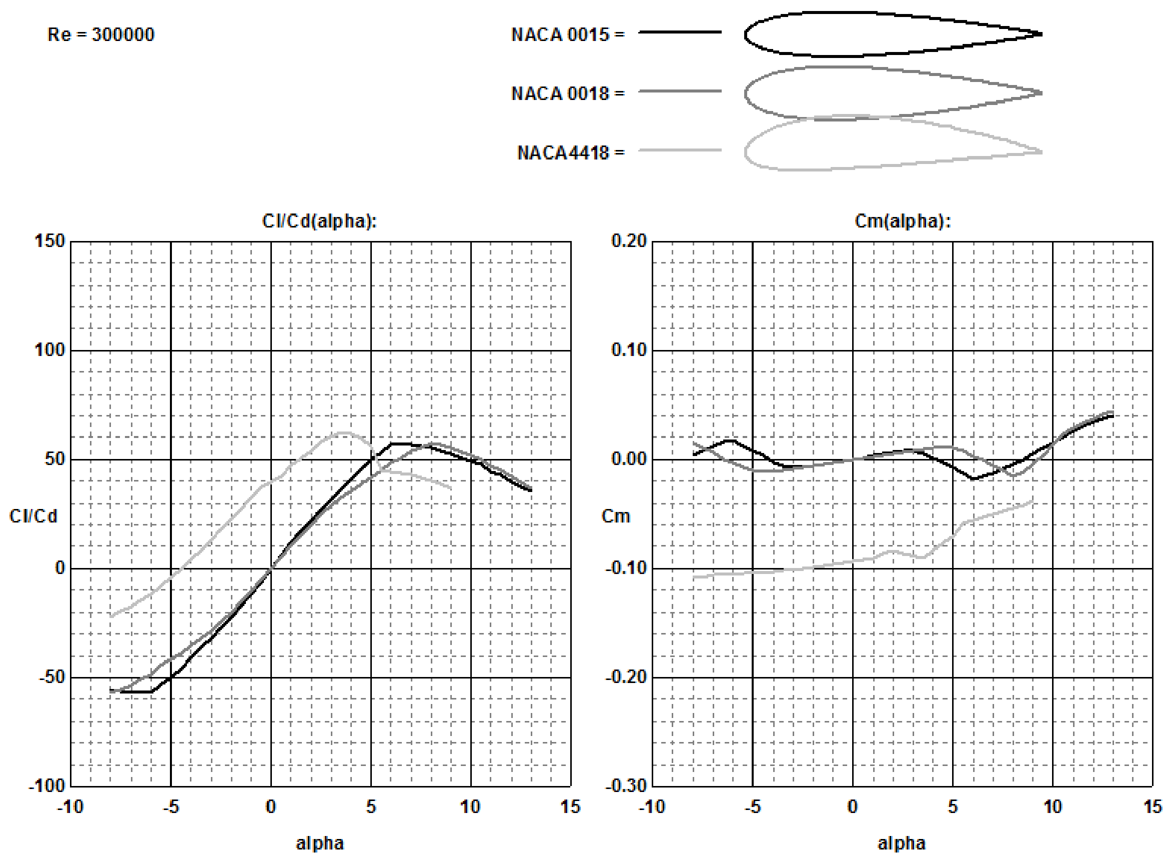

Fig. 12. Comparison of aerodynamic coefficients for NACA 0015, NACA 0018 and NACA 4418 profiles for number Re= 170000. (Profili v2.30a)

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SELECȚIA PROFILELOR DE PALĂ PENTRU TURBINELE EOLIENE DE PUTERE MICĂ ÎN FUNCȚIE DE PERFORMANȚA AERODINAMICĂ

Rezumat: Optimizarea performanței este una dintre preocupările majore din industria turbinelor eoliene și mai ales din doemniul turbinelor eoliene de putere mică, care sunt în mare parte găsite în zonele urbane. După cum ştim, zonele urbane au un flux turbulent al vântului, schimbări frecvente ale direcţiei de curgere și intensitate a vântului, rafale şi alte obstacole . Această lucrare se concentrează pe studiul performanţelor aerodinamice de diferitelor profile de pală, care sunt utilizate pe scară largă în construcția turbinelor eoliene de putere mică. Rezultatele obținute în urma analizei paletei au arătat că profilurile asimetrice sunt potrivite pentru turbine eoliene mici, deoarece acestea au cel mai bun raport portanță la rezistență aerodinamică într-o gamă largă de unghiuri de atac.

Emanuela SOUCA, PhD student, Dept. Design Engineering and Robotics, Technical University of Cluj-Napoca, Romania, ema13m@yahoo.com, Mobil: 0742.928.340;
Cornel CIUPAN, Prof. Dr., Dept. Design Engineering and Robotics, Technical University of Cluj-Napoca, Romania, phone: 0264.401.600.