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THE INFLUENCE OF THE DRAG DYNAMIC STALL IN THE VAWT STARTING EFFICIENCY

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ABSTRACT

This paper studies the behavior of a vertical axis wind turbine at the moment of starting. In order to capture this behavior a series of numerical analysis with CFD methods was performed. The complexity and the unsteady characteristics of this type of wind turbine can be study by using the unsteady RANS models.
The flow patterns in this case were studied for a single representative value of tip speed ratio (TSR=1). To determine the influence of dynamic stall, two cases were study: one case with a NACA 0018 isolated airfoil and one case with the same airfoil in configuration on vertical axis Darrieus type wind turbine. Because of the low Reynolds number, the SST transition model was use to capture the transition from laminar to fully turbulent flow.
All the simulations were done in 2D with two domains, rotor and stator. The mesh was generated with ICEM CFD using structured blocking. Results show an interesting phenomenon in flow around a vertical axis wind turbine. This phenomena we have called it "drag dynamic stall". To see exactly the influence of this flow characteristic we represented the drag coefficient variation with the angle of attack for this two studied cases.

Keywords: VAWT, RANS, 2D, Dynamic stall

NOMENCLATURE

Cm	moment Coefficient;
R	rotor Radius;
N	number of blades;
c	airfoil chord;
γ	intermittency;
Re	reynolds Number;
Cl	lift Coefficient;
Cd	drag Coefficient;
λ	tip Speed Ratio;
y^+	dimensionless wall distance;
$Re_{\theta t}$	transition Reynolds Number;
ω	angular velocity.

INTRODUCTION

Wind represents the movement of air masses from a high pressure area towards a lower pressure area and is caused by unevenness in the Earth crust heating by the sunlight. Because of this, wind power is regarded as indirect solar energy [1]. Wind power varies with altitude, in particular due to the planetary boundary layer. Exhaustion of oil and gas resources, corroborated with pollution related concerns, has led to an increased attention towards renewable energy sources which are considered to be non-polluting [2]. In order to harness wind energy, turbines are used to either deliver mechanical work or - more frequently - electricity by using a tailored generator.

The turbine studied in this paper is a classical embodiment of G. Darrieus's invention [3] from 1920. Due to the fact that it relies on the lift force - rather than the drag force as is the case with Savonius turbines - the efficiency is high and its effectiveness does not depend on wind direction. The development of this turbo-machinery has progressed along with the oil crisis in the '70s. Important references in the field belong to I. Paraschivoiu [4], which developed a numerical method for estimating wind turbine efficiency.

Various studies have been published, regarding influence of the number of blades, airfoil chord and wind speed on wind turbine efficiency. M.R. Castelli [5] has particularly studied the influence of number of blades on the turbine efficiency. Using a constant value for the solidity factor he was capable to determine the chord for each individual case. S. Li and Y. Li [6] have developed a series of numerical analysis regarding the solidity effects and concluded that a higher solidity factor will lead to greater power at low tip speed ratios (TSR).

However, as useful these studies may be, the interdependencies and influences of numerous aerodynamic phenomena makes efficiency estimations difficult for this type of wind turbine. Moreover, current research focus on more subtle aspects of turbine flow such as dynamic stall. McCroskey [7] was one of the first to propose a semi-empirical method which perfected by using experimental data on an isolated airfoil. Other such methods have since been proposed and developed, a comprehensive review of those models dealing with dynamic stall in VAWT has been made by Reddy and Kaza [8]. In spite of the concept simplicity, the interactions between the vortices shed by blades, especially at low Reynolds numbers, can be very complex and difficult to predict. A first remark is that velocity variations near the blades, depending on their positioning, is significant and leads to interacting flow structures.

Note that although complex, these variations are periodic with a period depending on the number of blades N, as described in Eq.1.

$$\varepsilon = 2\pi/N \tag{1}$$

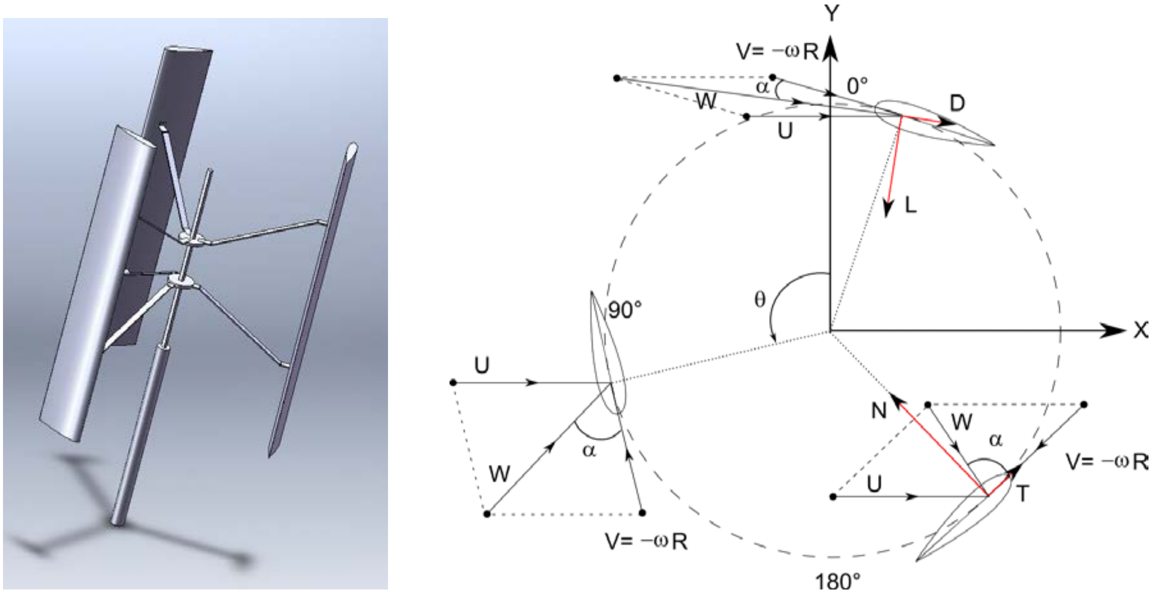


Figure 1 - Geometrical model and the principal's forces on a vertical axis wind turbine

Another method for predicting this phenomenon is numerical based on the potential linearization the Navier-Stokes equation system. Representative papers regarding these methods belong to Scrieda [9] and Allet [10].

This turbine solution has an operation range limited by the static and the dynamic stall. Although, to some extent, the dynamic stall has some positive influences on its efficiency, at lower values of tip speed ratio, the small vortex shedding can lead to problems such as noise, vibrations and even fatigue [11]. In one of his papers, Larsen [12] shows that dynamic stall is predominantly characterized by flow separations on the inner side of the airfoils. This separation can lead to lift and drag instabilities and leads to high momentum coefficient oscillations which have a high hysteresis - which also depends on the angle of attack [13].

In this paper we study, using CFD, the behavior of an H-type vertical axis wind turbine at the starting moment. This study was carried out at the constant TSR value of one. In order to discern between static and dynamic stall, a comparison between an isolated and one airfoil in turbine configuration was made, both cases having the same Reynolds number.

NUMERICAL METHODS

In order to understand the physical phenomena involved in dynamic stall, two cases were considered. Therefore, the first case is that of an isolated airfoil and the second reveals the behavior of the same airfoil, at the same Reynolds number, but in the context of the Darrieus VAWT. Both cases were studied using fully viscous 2D CFD methos. The airfoil taken into consideration is the NACA 0018. The characteristics of the wind turbine are presented in Table 1. Furthermore, the computational domains are depicted in Fig.2. ANSYS Fluent commercial code was used in solving the cases.

Table 1 : The main geometrical features for the vetical axis wind turbine

Airfoil NACA 0018						
Wind speed	Radius	Chord	Number of blades	Characteristic height	TSR	Solidity
8[m/s]	1.8[m]	0.6[m]	3	4.5[m]	1	0.5

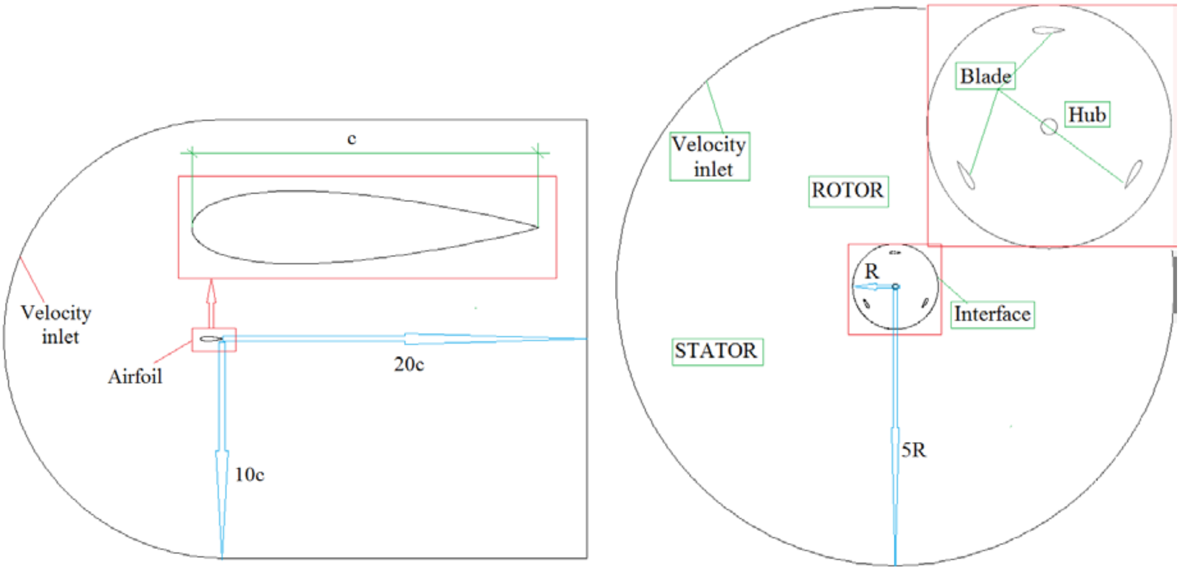


Figure 2 :- The static and rotating fluid domains

Figure 4 presents the computational mesh, structured using blocking as seen in Fig.3. The comptational mesh was created by considering that the y+ value near the walls must be lower than or equal to one unit - as recommended for the k-omega turbulence models. Therefore the order of magnitude of the cells near all walls is 1 e-05 m and the growth ratio is 1:1. The number of cells for each domain is detailed in Table 2.

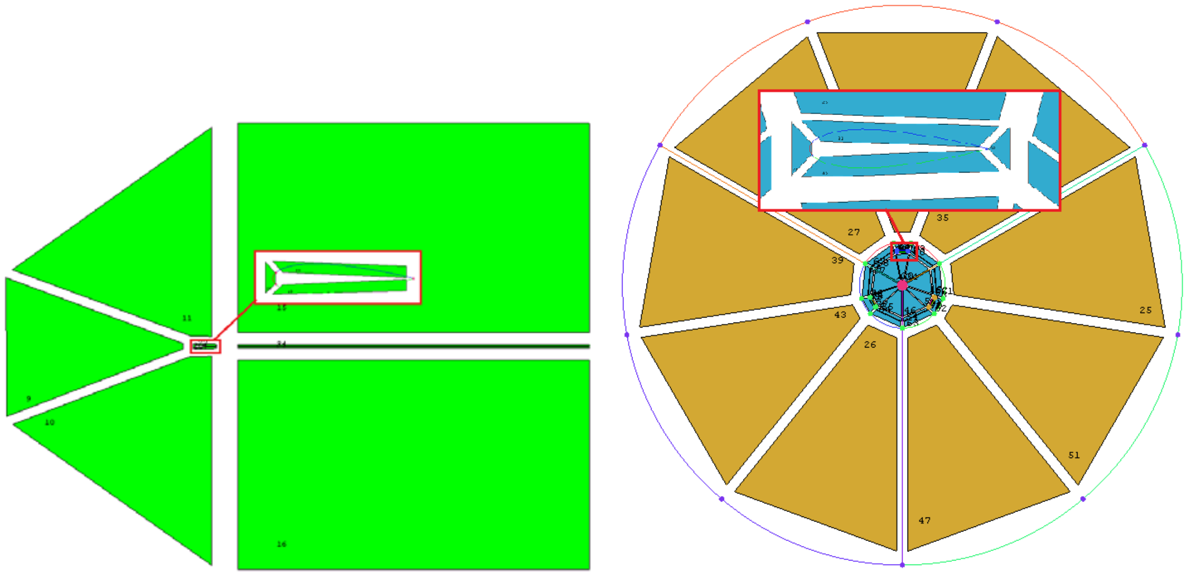


Figure 3:- Icem CFD blocking structure for studied cases

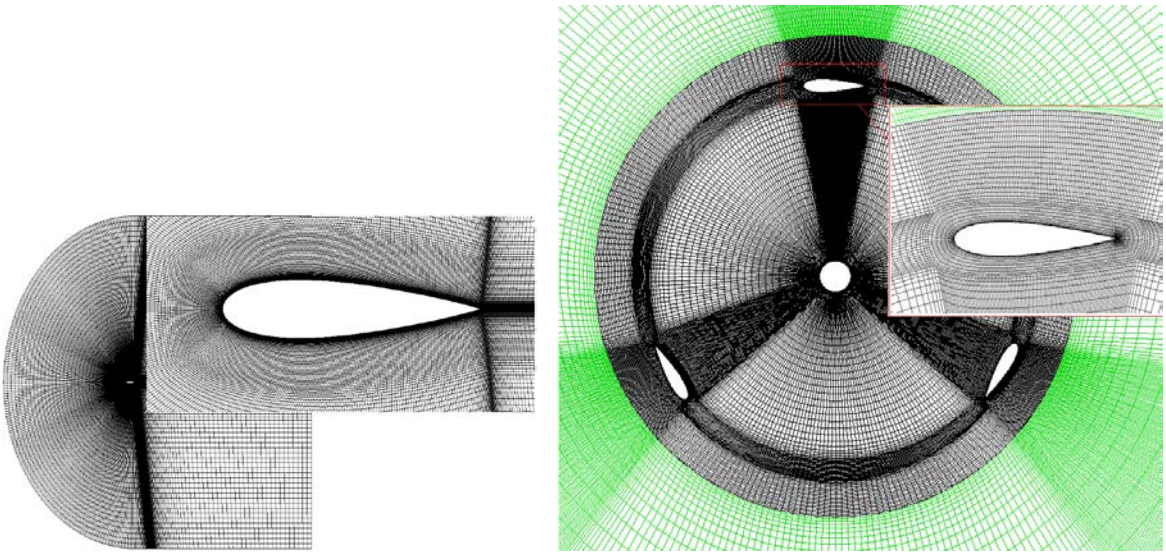


Figure 4 :- The mesh for airfoil and VAWT

Table 2: Number of cells

Case		Number of cells
Airfoil		~150000
VAWT	Rotor	~250000
	Stator	~150000

In order for simulations to be as close to the real flow as possible, the boundary conditions presented in Fig.2 were used. Both cases were simulated using pressure based solvers with SIMPLE (semi-implicite method for pressure link equation) method used for spatial discretization. The value of the freestream velocity is of 8m/s and is correlated such as the Reynolds number is the same in both cases.

In the case of isolated airfoil, the computational domain spans for 30 chords whereas in the case of the wind turbine, the stator domain spans approximately 5 times the radius of the rotating domain.

Because of the fact that case studies occur at low Reynolds numbers, a turbulence model which accounts for transition had to be used. Therefore the SST transition model [14] was used, having four transport equations. The first two equations are from the classic k-omega formulation and the last two equations are used to model the transition between the laminar and turbulent regimes.

The intermittency transport equation can be written as:

$$\frac{\partial(\rho\gamma)}{\partial t}+\frac{\partial(\rho U_j\gamma)}{\partial x_j}=P_{\gamma 1}-E_{\gamma 1}+P_{\gamma 1}-E_{\gamma 2}+\frac{\partial}{\partial xj}\left[\left(\mu+\frac{\mu_t}{\sigma_\gamma}\right)\frac{\partial\gamma}{\partial x_j}\right] \tag{2}$$

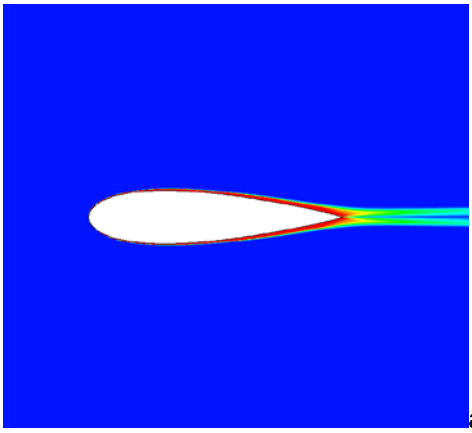
and the impulse thickness Reynolds number transport equation, $\widetilde{\mathrm{Re}}_\theta$

$$\frac{\partial(\rho\widetilde{\mathrm{Re}}_\theta)}{\partial t}+\frac{\partial(\rho U_j\widetilde{\mathrm{Re}}_\theta)}{\partial x_j}=P_\theta+\frac{\partial}{\partial x_j}\left[\sigma_\theta(\mu+\mu_t)\frac{\partial\widetilde{\mathrm{Re}}_\theta}{\partial x_j}\right] \tag{3}$$

The main advantage of this turbulence model is that it factors in the turbulence intensity of the upstream flow, the pressure gradients and leads to a more accurate boundary layer separation.

RESULTS

A good way to visualize the differences between the flow structures forming during the starting regime of the VAWT is to plot the vorticity contours for the airfoil at different angular positions. Figure 5 presents the contours for vorticity developed around the two airfoil cases. In Fig.6 the same positions are analyzed from the perspective of the streamlines.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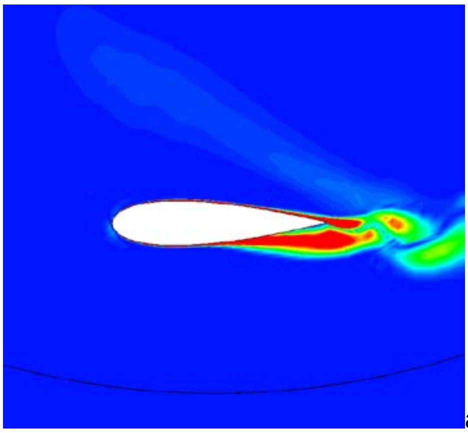
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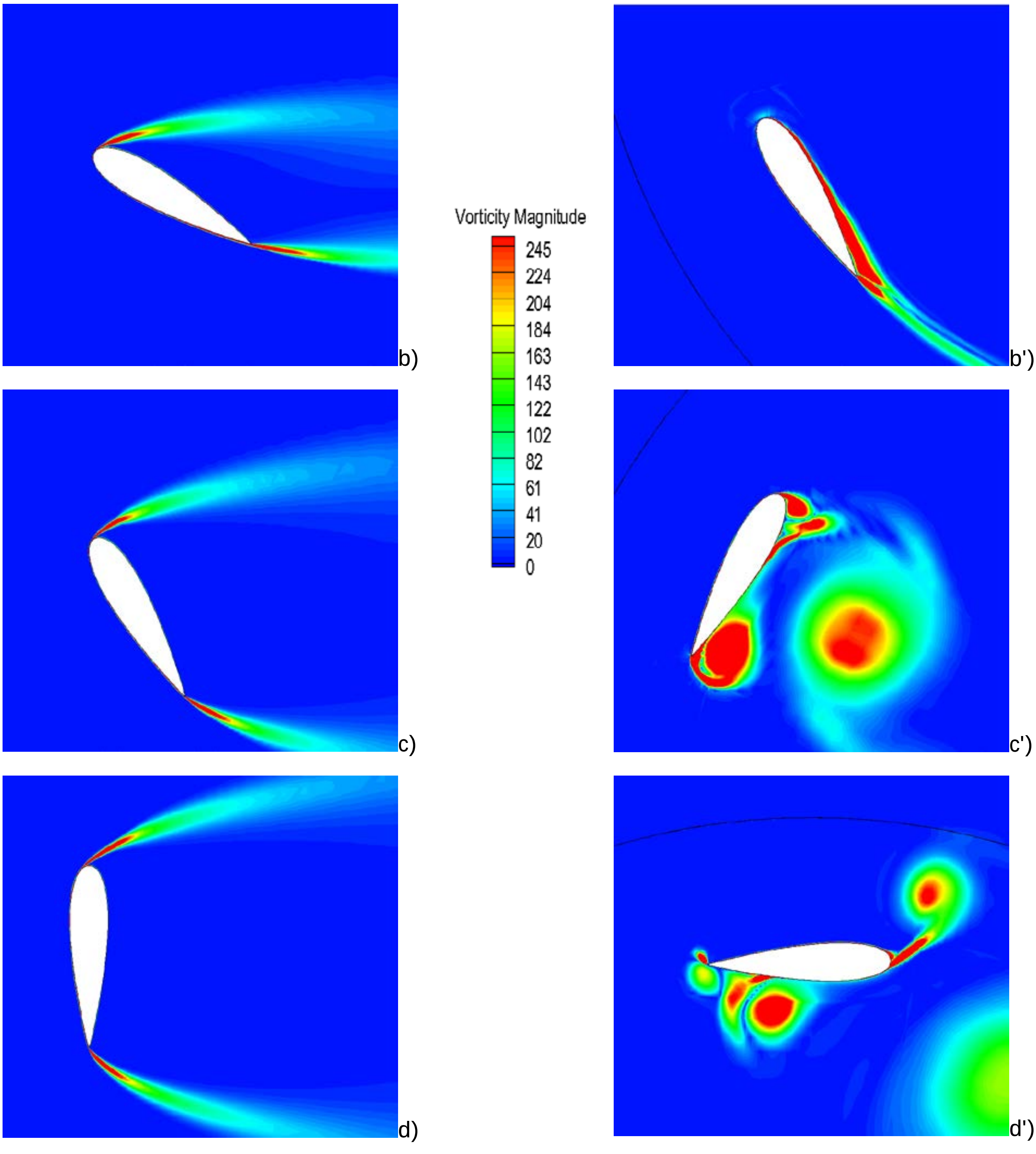
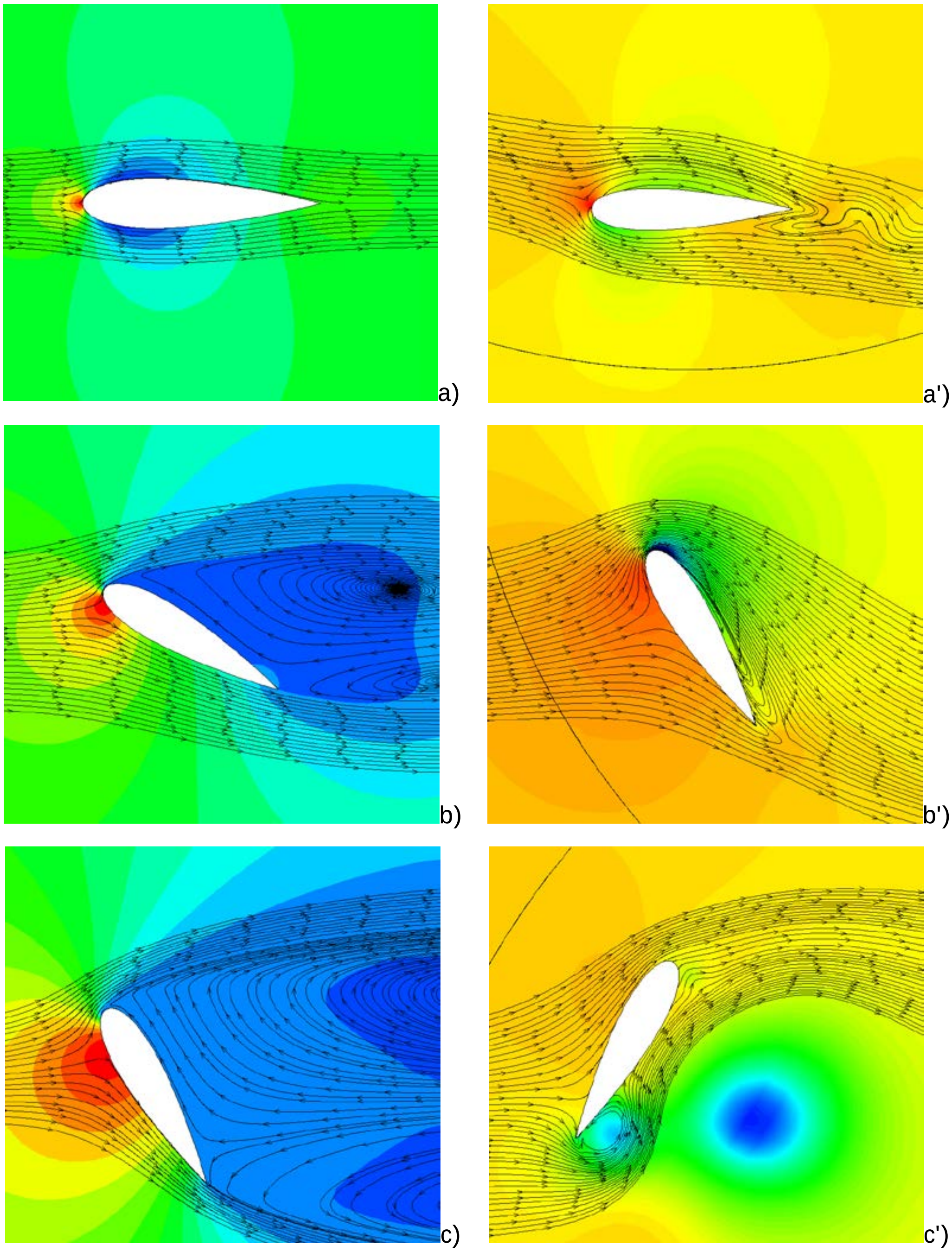


Figure 5:- Vorticity magnitude for:
a) Naca 0018 airfoil at 0°;b) Naca 0018 airfoil at 30°; c) Naca 0018 airfoil at 60°; d) Naca 0018 airfoil at 90°;
a') VAWT at 0°;b') VAWT at 30°; c') VAWT at 60°; d') VAWT at 90°;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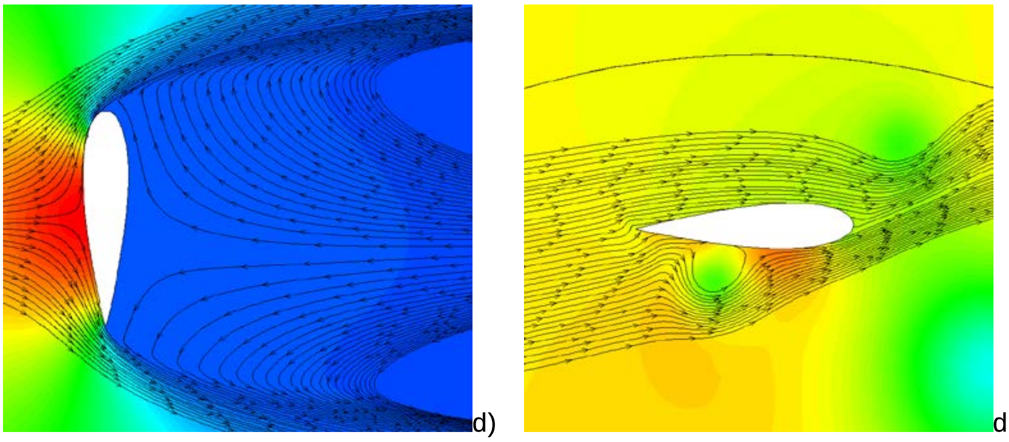


d) d')

Figure 6:- :- Streamlines for:
a) Naca 0018 airfoil at 0°;b) Naca 0018 airfoil at 30°; c) Naca 0018 airfoil at 60°; d) Naca 0018 airfoil at 90°;
a') VAWT at 0°;b') VAWT at 30°; c') VAWT at 60°; d') VAWT at 90°;

In Fig.7 we present the aerodynamic coefficients as a function of angle of attack for the isolated airfoil and for airfoil in turbine configuration.

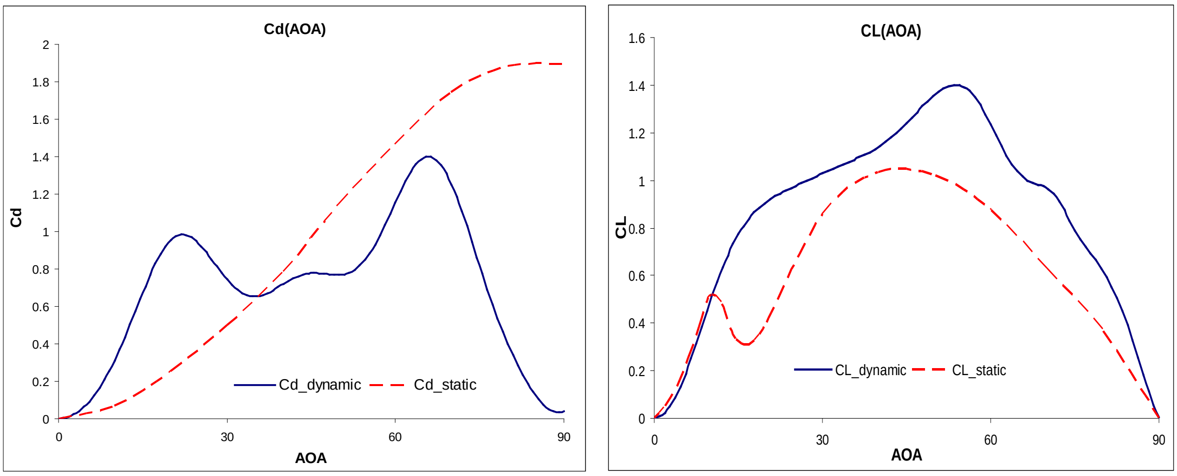
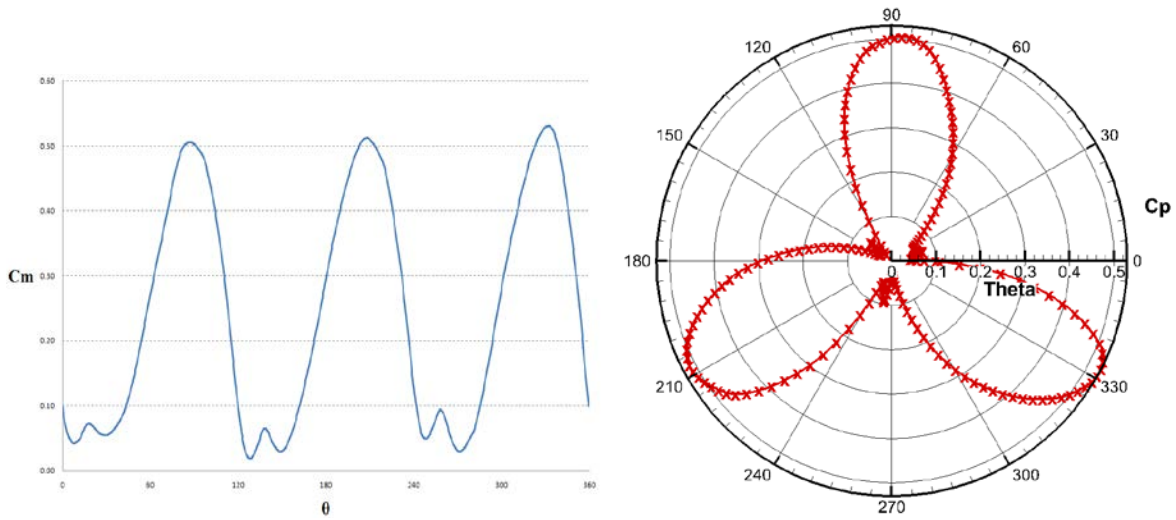


Figure 7:- Aerodynamic coefficients variation with angle of attack: Drag coefficient (a) and Lift coefficient (b)



a) b)

Figure 8:- The momentum coefficient evolution in time (a) and the power coefficient distribution radar plot for the entire VAWT assembly (b)

RESULTS

This paper presents a series of numerical CFD analyses in the attempt to capture the drag dynamic stall phenomenon. In order to highlight this behavior, both the flow around the isolated airfoil and the flow around a turbine mounted airfoil have been compared. The wind turbine configuration is a Darrieus H-type. All analyses were carried out using the transition corrected k-omega SST RANS model, due to the fact that the flow at the TSR considered is typically at low Reynolds numbers.

At a TSR equal to one unit, the dynamic stall was obtained and also correlated with a relative decrease of the aerodynamic drag. In order to illustrate this drag dynamic stall, the drag coefficients for the isolated and turbine mounted airfoil were compared.

Experimental confirmation of the numerical results will be sought further in the wind tunnel of the NRDI Comoti, where a model of up to 1m height can be tested at freestream speeds of up to 20 m/s.

REFERENCES

[1] Wind Directions, Volume XX,nr5, 2001

[2] Renewable energy world, jan 1999

[3] *L. J. Hagen and M. Sharif*, “Darrieus wind turbine and pump performance irrigation pumping”, Report No DOEIARS-3707-20741 I81 11, May 1982

[4] *I.Paraschivoiu*, “Wind turbine design – with emphasis on Darrieus concept”, Ecole Polytechnique de Montreal,2002

[5] *M.R. Castelli*, “Effect of blade number on a straight – bladed vertical axis Darrieus wind turbine” ,World Academy of Science, 61,2012

[6] *S.Li, Y.Li* , “Numerical study on the performance effect of solidity on the straight – bladed vertical axis wind turbine”, Power and energy Engineering Conferance, 2010

[7] *W.J. McCroskey*, “Some Current Research in Unsteady Fluid Dynamics”, Journal of Fluids Engineering, vol.99, pp. 8-39

[8] *T.S.R. Reddy, Kaza*, “A Comparative Study of Some Dynamic-Stall Models”, NASA Tech Memo 88917, 1987

[9] *Y. Shida, K. Kuwahara, H. Takami*, "Computation of Dynamic Stall of a NACA-0012 Airfoil", AIAA Journal, vol.25,no.3, 1987, pp408-413
[10] *A.Allet, I. Paraschivoiu*, "Aerodynamic Analysis of the Darrieus Wind Turbines Inclunding Dynamic-Stall Effects", AIAA Journal of Propulsion and Power, vol.4, no.5, 1988, pp. 472-477
[11] *C.P. Butterfield, A.C. Hansen, D. Simms, G. Scott*, "Dynamic stall on wind turbine blades", Windpower'91, Confererence and Exposition, Palm Springs, California, september 24-27, 1991
[12] *J.Larsen,S. Nielsen, S. Krenk* , "Dynamic stall model for wind turbine airfoils", Journal of Fluids and Structures, vol. 23, no.7, 2007, pp 959-982
[13] *Y. Shida, K. Kuwahara, H. Takam J.A. Ekaterinaris, M.F.Platzn*, "Computational prediction of airfoil dynamic stall", Progress in Aerospace Sciences, vol.33, no. 11, 1998, pp 759-846.
[14] *R.B.Langtry, F.R. Menter*, "Transition modeling for general CFD application in aeronautics", AIAA 2005-522