NUMERICAL SIMULATION OF VAWT FLOW USING FLUENT*

Ion MĂLĂEL[1], Horia DUMITRESCU [2]

This paper refers to the study of flow in vertical axis wind turbines using numerical methods for gas dynamic calculation (CFD). It is presented a comparative study between two fundamentally different methods, RANS (stationary mode) and URANS (in non-stationary regime) - the last being more scientifically rigorous. Simulations were performed using the commercial CFD code ANSYS-Fluent and computing grid was generated with ICEM CFD program. The method used involves meshing domain structure calculation and k-ω SST turbulence model. Simulation results show, contrary to the expectations, that URANS method (which accurately captures the physical phenomena) estimates a better efficiency for vertical axis wind turbine than the efficiency estimated using RANS method. The implications of these conclusions are many and are liable to improve understanding of the functioning of vertical axis turbines.

Key words: Darrieus, wind turbine, VAWT, RANS, CFD, ICEM

Nomenclature

VAWT – vertical axis wind turbine;
RANS, URANS – Reynolds Average Navier-Stokes, unsteady Reynolds Average Navier-Stokes;
CFD – computational fluid dynamics;
P_w [W] – wind power;
C_{pT} – the turbine power coefficient;
P_T [W] – wind turbine power;
M [Nm] – momentum;
ω [m/s] – radial velocity;
ρ [kg/m^3] – density;
S[m^2] – surface;
V_{inf} [m/s] – upstream velocity;
L[m] – reference length;
C_m – momentum coefficient;

[1] Eng., Faculty of Aerospace Engineering, University POLITEHNICA of Bucharest, Romania, e-mail: ionmalael@yahoo.com
[2] Prof., Institute of Mathematical Statistics and Applied Mathematics "Gheorghe Mihoc-Caius Iacob", Romanian Academy, Bucharest, e-mail: horia.dumitrescu@yahoo.com
The results presented in this article were obtained withthe support of Ministry of Labour, Family and Social Protection through Sectorial Operational Programme Human Resources Development 2007-2013, Contract no. POSDRU/107/1.5/S/76909.

$\lambda = TSR$ – tip speed ratio;
R[m] – wind turbine radius;
N – number of blades;
c[m] – blade's chord;
σ – solidity;
H [m] – wind turbine height;
SST – shear stress transport;
k – turbulence kinetic energy;
ε – dissipation;
ω – specific dissipation rate;
Y^+ – non-dimensional wall distance;
Y – the distance to the nearest wall;
τ_w – the wall shear stress;
υ – the local kinematics viscosity;

1. Introduction

Because of the negative environmental effects of fossil fuel based power generation, interest in renewable energy resources has increased over the years.
Darrieus vertical axis wind turbine (VAWT) is a classic example of renewable energy powerplant. Invented in 1920's [1], the Darrieus VAWT is a lift based wind turbine, as opposed to the Savionius class of VAWT which is based on drag and tends to be less efficient.

The current paper aims to explore, on one hand, the parameters that factor in the overall efficiency of the Darrieus turbine and, on the other, to determine the best ways to carry out CFD simulations for this particular class of turbines.
While it is known that unsteady RANS (URANS) simulations lead to more physically sound results, they are often replaced by steady RANS simulations which are less time consuming. For each class of CFD problems there are sets of "best practice" rules, based on the extensive experience in the field. It is therefore a purpose of this paper to provide an insight in the field of Darrieus VAWT simulations by outlining the differences in the RANS-URANS simulations. From a numerical stand point, CFD problems can be categorized into two classes steady or unsteady (although it also needs to be stated that all turbulent flows are somewhat unsteady in nature).

Steady state, in which the flow characteristics are – as the name suggests – steady (i.e. do not vary significantly in time). A fundamentally different class of problems are represented by those in which the flow field has a variation in time, called unsteady – hence the name URANS. It is often the case that the variations are governed by a specific frequency or period. However, it needs to be pointed out that the mere periodic movement (such as the one in rotating machinery) does not mean that the flow is unsteady.

The CFD solver used, Ansys FLUENT, allows the possibility of running both RANS and URANS simulations.

The literature survey reveals that practically all the relevant parameters, such as the influence of the number of blades, chord, airfoil thickness, wind speed, have been studied extensively in order to determine their influence on the turbine efficiency. Studies, such as I.Paraschivoiu [2,3], use numerical methods for determining the efficiency of wind turbines.

M.R. Castelli [4] studied the influence of the number of blades on a wind turbine performance. Using a constant value of the solidity factor, he was able to determine the profile chord to each case separately.

S.Li and Y. Li [5] have developed a series of numerical analyzes on the solidity effects on a vertical axis wind turbine and concluded that a high solidity can produce maximum power at lower TSR.

Recently, Danao et. all [6] studied the effects of thickness of the airfoils for turbine blades.

Ferreira concludes in [7], that the flow in this turbine has an unsteady behavior because the incidence angle varies depending on blade position and on relative speed and Reynolds number.

Wand and Tao [8] performed an analyses using a RANS model with SST turbulence model concluding that could lead to the phenomenon of dynamic stall, advanced CFD methods such as LES should be used.

In this paper, two sets of CFD analyses were performed, steady and unsteady. The chosen turbine architecture was a Darrieus vertical axis wind turbine with three blades. The analyses were performed at a single TSR setting, trying to determine the differences between the RANS and URANS methods both from a physical stand point (performance comparison) and also numerical (convergence criteria, convergence time, troubleshooting etc).

2. Numerical methods

2.1. General consideration

The generally accepted theory for power estimation in wind turbines is provided in [9].

$$P_{wind} = \frac{1}{2}\rho S V_{\inf}^{3} C_p \quad (1)$$

where Cp - power coefficient, for the ideal case is 1. (the all wind energy is extracted by the turbine).

However, it was shown by Betz[10] that this coefficient can not exceed the value of 0.593.

$$C_{pT} = \frac{P_T}{P_{wind}} = \frac{M \cdot \omega}{\frac{1}{2}\rho S V_{\inf}^3} = \frac{\frac{1}{2}\rho S V_{\inf}^2 L C_m \omega}{\frac{1}{2}\rho S V_{\inf}^3} = C_m \cdot \frac{L \cdot \omega}{V_{\inf}} = C_m \cdot \lambda < 0.593 \cong \frac{16}{27} \quad (2)$$

To determine the optimal chord of a turbine blade we define the solidity factor. Consensus on the mathematical expression of this parameter is not reached at this point since, depending on the author, the solidity can be expressed in the in several forms, either relative to the turbine rotor radius or diameter or to the circle length ($2\pi R$).

$$\sigma = \frac{Nc}{R} \; or \; \sigma = \frac{Nc}{2R} \; or \; \sigma = \frac{Nc}{2\pi R} \quad (3)$$

Using the above equation (3), a wind turbine design was reached. The working parameters are listed below.

$$\begin{aligned} &\lambda = 3 \\ &R = 1.8m \\ &H = 3.6m \\ &\left.\begin{aligned}\sigma &= 0.25 \\ N &= 3\end{aligned}\right| \Rightarrow c = 0.3m \\ &\mathrm{Re} = 1.2 \cdot 10^6 \\ &Airfoil\ NACA0018 \end{aligned} \quad (4)$$

<u>2.2.1 Steady RANS and unsteady URANS CFD simulations</u>

Using the guidelines of [11] which provide a generalized set of CFD best-practices, we opted for the use of the k-omega SST [12] turbulence model, as implemented in the Ansys Fluent [13] code. The advantage of this model is the blending function for combining the Wilcox k-omega model [14], which models more precisely the boundary layer flow, and the standard k-epsilon [15] model which is much more stable in the far field region. The k-epsilon standard model utilizes the assumption of turbulence isotropy – i.e. the shear stresses (for the three Cartesian directions) are considered equal. This assumption is not valid inside the boundary layer and therefore, under adverse pressure gradients, the production term in the TKE transport equation is overestimated. This is because the production term, instead of being calculated on the differences between the shear stresses, is calculated on the mean shear stress. It is therefore a good thing to avoid, in the boundary layer, the use of the k-epsilon models since they have a tendency to not predict the boundary layer separation. Hence, by using the k-omega SST model, the good results of the specific dissipation models (k-omega) are obtained while maintaining the far field stability of the k-epsilon models.

The discretization schemes chosen, in all cases, was second order upwind since the numerical diffusivity of this scheme is lower and produces more reliable results.

Based on the known operation of Darrieus wind turbines, a CFD strategy was developed for each of the two simulation sets. For the steady state simulations, a number of 36 individual CFD cases was run. Each of the individual simulation was conducted at 10° increments.

For the unsteady URANS simulation, a different approach was needed. The angular velocity was imposed together with the "moving mesh" setting. The time step was chosen in such a manner that, for each time step, the mesh will only rotate one cell – thus enhancing the continuity of the two domains (the stationary domain and the rotating domain which contains the actual turbine geometry).

The transport equation for turbulent kinetic energy k is written as follows:

$$\frac{\partial k}{\partial t} + \overline{u}\frac{\partial k}{\partial x} + \overline{v}\frac{\partial k}{\partial y} + \overline{w}\frac{\partial k}{\partial z} = \Gamma_k\left(\frac{\partial^2 k}{\partial x^2} + \frac{\partial^2 k}{\partial y^2} + \frac{\partial^2 k}{\partial z^2}\right) + \widetilde{G}_k - Y_k \tag{5}$$

Also the transport equation for specific dissipation ω has the following form:

$$\frac{\partial \omega}{\partial t} + \overline{u}\frac{\partial \omega}{\partial x} + \overline{v}\frac{\partial \omega}{\partial y} + \overline{w}\frac{\partial \omega}{\partial z} = \Gamma_\omega\left(\frac{\partial^2 \omega}{\partial x^2} + \frac{\partial^2 \omega}{\partial y^2} + \frac{\partial^2 \omega}{\partial z^2}\right) + G_\omega - Y_\omega + D_\omega \tag{6}$$

where:

Γ_k and Γ_ω = The effective diffusivities for k and ω;

D_ω^+ = the positive portion of the cross-diffusion term;

$\widetilde{G}_k$ = the production of turbulence kinetic energy;

G_ω = the production of ω.

Geometry definition

Although the Darrieus VAWT is a three-dimensional object, in order to cut the computation time, a series of simplifications were carried out. Therefore, the simulations are so-called "two dimensional" cases. Two dimensional cases are, in fact, periodic three-dimensional cases with linear periodicity on the top/bottom boundaries. The height of the domain is implicitly set in the reference length menu.

The full geometry of the current VAWT is depicted in Fig.1.

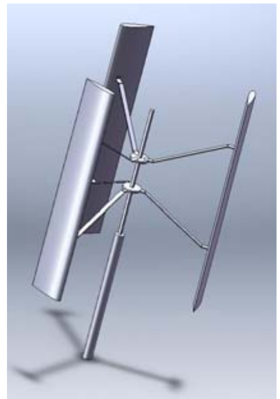


Fig. 1. 3D geometric model of vertical axis wind turbine

The two-dimensional geometry and domain – derived from this 3D geometry – is presentd in Fig.2. The computing domain consists of two fields with an interface at the boundary between them. The most important sub-domain is the rotor domain having a radius of R = 1.8m. The stator domain is 20 times larger than the rotating domain, as per [16], in order to allow the vortices shed off the wind turbine surfaces to dissipate before encountering the outer boundary. This helps prevent the so-called "boundary effect" which may interfere with the accuracy of the simulation.

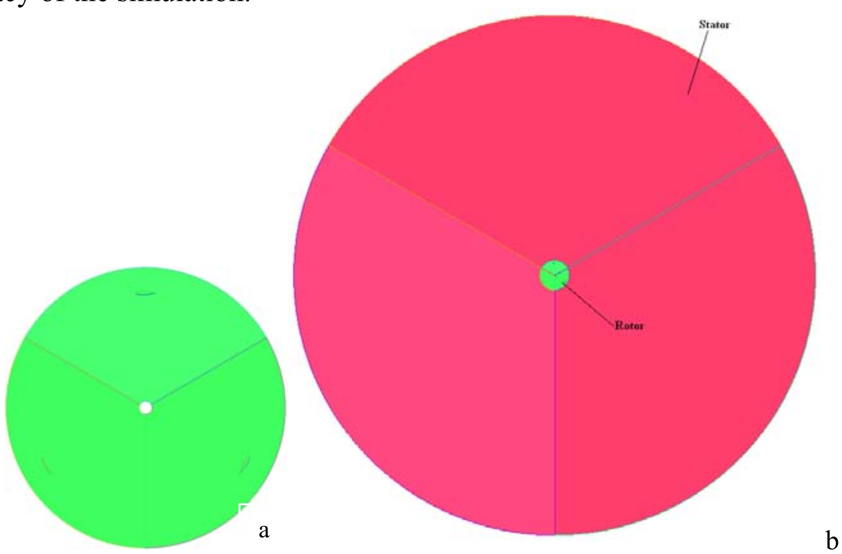


Fig. 2. Computing domain with the two sub-domains:
a. The inner rotor – containing the turbine geometry; and b. the surrounding stator providing space for eddy dissipation and insuring an appropriate distance between the interest surfaces and the outer boundary.

2.2.2. Computational mesh and boundary conditions

As stated before, the mesh is structured around a quad blocking, generated with the Ansys ICEM-CFD software.

In order to capture the aerodynamic phenomena occurring in the boundary layer – which is critical for understanding the VAWT aerodynamics – the mesh size was carefully controlled near all wall boundaries. The criterion used was to refine the mesh for a thickness equivalent to y^+=30, as recomended in [17] in order to maximize the potential of the SST model. Beyound y^+=30, the k-epsilon model takes effect (due to the blending function).

$$y^+ = y\frac{\sqrt{\frac{\tau_w}{\rho}}}{\upsilon} \quad (7)$$

Because the actual computation of the y+ value can only be made after the simulation has converged, in post-processing, another estimation was used to determine the rough size of the first cell. The equation is semi-empirical, as described in [18].

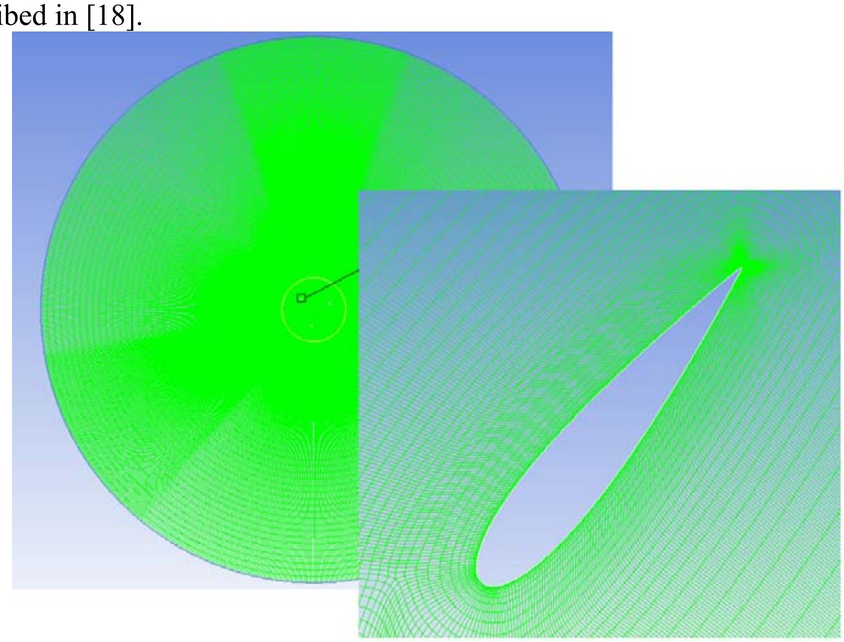


Fig. 3 Mesh structure near one of the three airfoils of the wind turbine

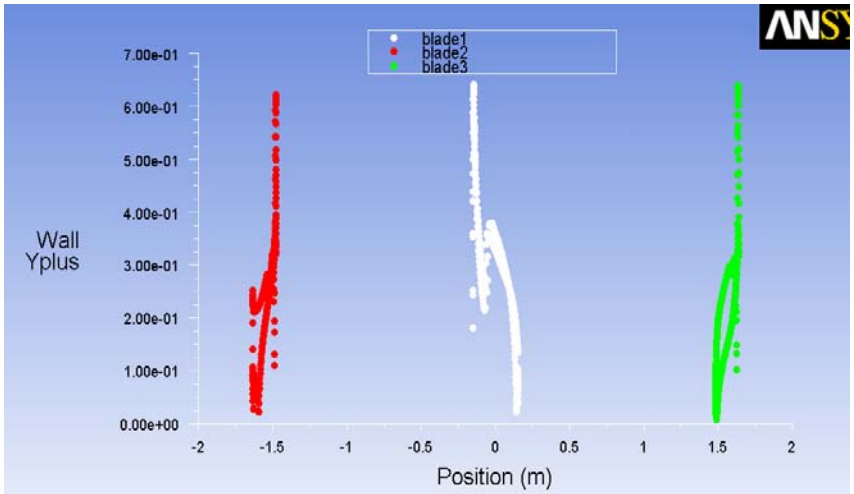


Fig. 4 The actual value of y + for all three blades, as computed by the solver

As proven in Fig.4, the initial estimate for the y+ was conservative, each of the blades having a good value, well below the limit of 1.

In Fig. 5 the generic boundary conditions for these cases are featured.

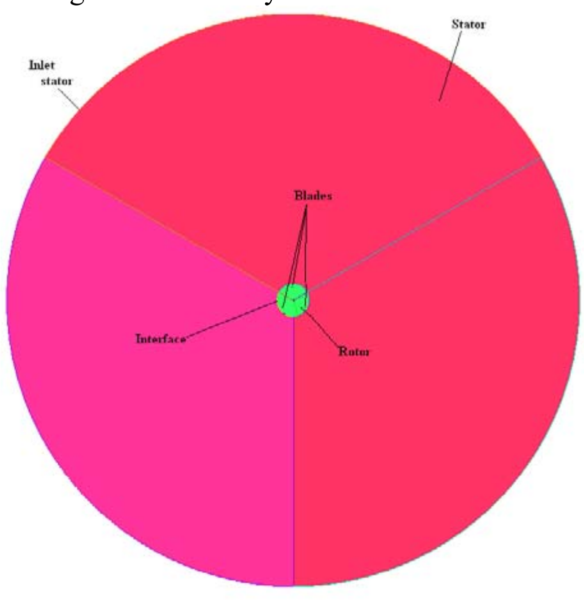


Fig. 5 The generic boundary conditions for the case setup

The boundary conditions were imposed so that the flow will closely resemble the natural conditions found in real life applications. Therefore, the inlet velocity was imposed at 6 m/sec and a rotation period of 10 rad/sec for the rotor domain. This corresponds to a tip speed ratio of 3, which is cosidedred the optimal working condition for the Darrieus VAWT.

Because the flow model differs for each of the numerical methods used, RANS and URANS, different convergence criteria were applied in order to optimize the result quality.

For the 36 individual steady (RANS) cases, two criteria were employed: In addition to the residual magnitude condition of 10^{-6}, for each of the equations of the SST model, the stability of the drag force on each airfoil was sought. This is because drag, particularly pressure (induced) drag, is tied to flow steadiness which is one of the assumed characteristics for the solution.

For the unsteady (URANS) case, the residual magnitude condition was also applied. However, instead of monitoring the drag parameter, a different secondary criterion was used. Since, in this case, the turbine is assumed to be rotating, the momentum magnitude is known to be periodical i.e. it has a certain, constant, period of oscillation. It is therefore sensible to monitor the momentum parameter, calculated over the three rotor blades, and consider the convergence only when the variation of this parameter appears to be periodical with a constant amplitude and frequency. The solution was considered converged after 8 full cycles that show less than 5% differences in amplitude. One flow period in this case equaled 0.72 sec (flow time) and corresponds to a 2-day runs on a 4-processor configuration. Figure 6 depicts the evolution of the momentum coefficient for the unsteady case.

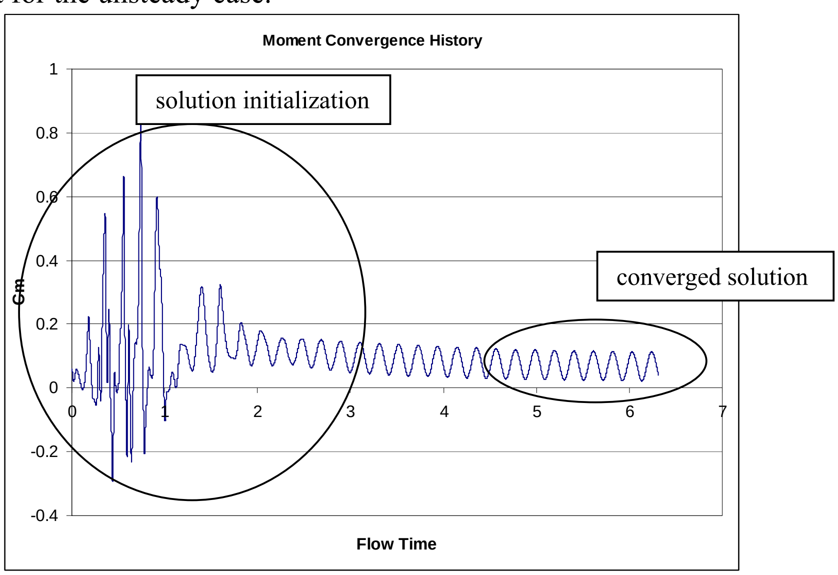


Fig. 6 Momentum coefficient convergence evolution in time for the unsteady URANS case

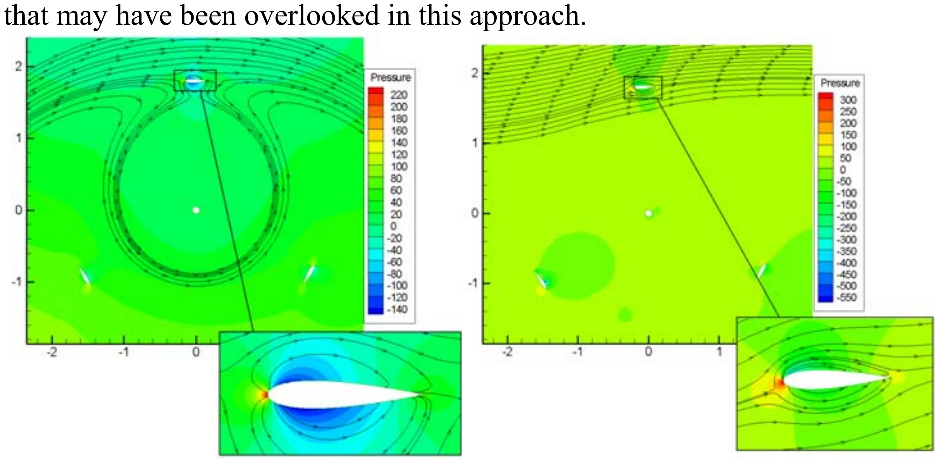
3. Results and discussions

The classical plot charts for the streamlines are presented in figure7-10. This figures shows the flow fields in four representative angular positions, at 0º, 30 º, 60 º and 90 º.

At low angular settings, below 30 º, the flow field is fairly uniform and the wake of the advancing blade can be seen to influence the flow near the following blade. As the rotor turns between 30 º and 60 º, the flow field begins to “polarize” into two diametrically opposed regions. A high speed region enveloping the single advancing blade – which does no longer “feel” the wake of the previous blade- and a low speed region delimited by the other two blades (which are, largely, in symmetrical positions). This behavior later reduces as the rotor turns towards 90 º and the flow field tends to become uniform. It is interesting to observe that, in this case (at 90 º), the mere fact that the top blade looses the downwash wake of the previous blade leads to a slight acceleration of the fluid in its region. However, this acceleration works “against” the turning of the rotor, slowing it down.

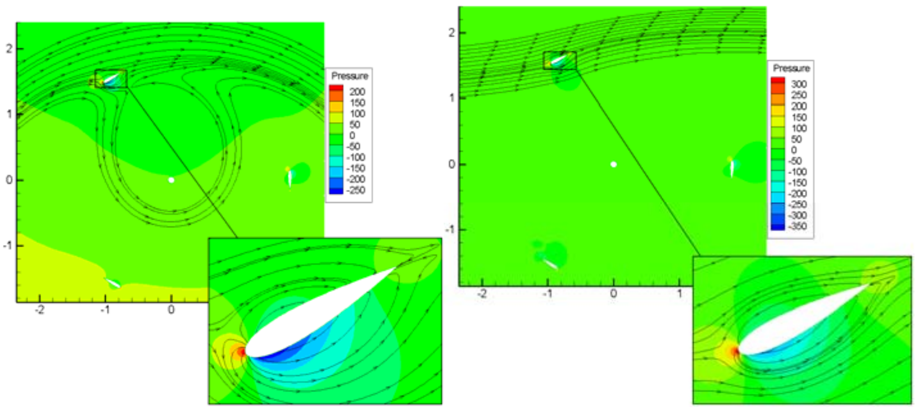
A better way to analyze this pattern of behavior is to plot a momentum coefficient vs. angular position chart, similar to the one in Figure 11.
From it, it becomes clear that the global tendency of the rotor is to accelerate in the 0 º- 60 º region where it displays a local maximum and then to decelerate as the rotor spins to 90 º.

Although the 36 steady RANS individual cases helped understand the reasons for which the momentum coefficient of the Darrieus VAWT varies in time – and consequently in angular position – there are some other flow effects that may have been overlooked in this approach.



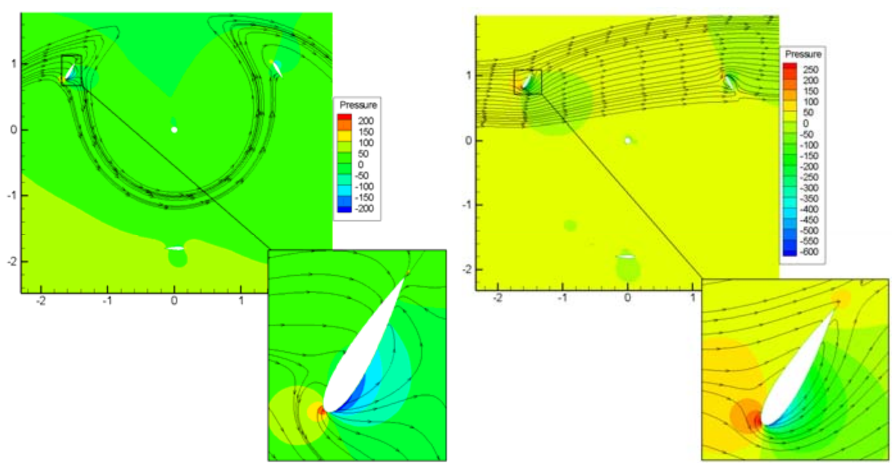
a) b)

Fig. 7 Streamlines for 0 degrees, $\lambda = 3$:a) RANS;b)URANS;



a) b)

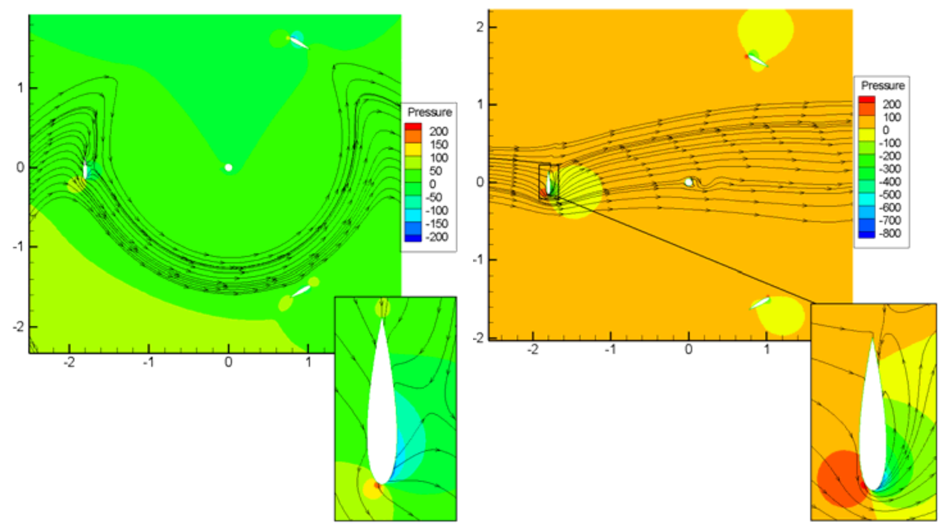
Fig. 8 Streamlines for 30 degrees , $\lambda = 3$:a) RANS;b)URANS;



a) b)

Fig. 9 Streamlines for 60 degrees , $\lambda = 3$:a) RANS;b)URANS;

The merit of the unsteady URANS simulation is that effects such as blade-wake interactions and periodic vortex shedding such as the Karman vortex street can be factored in and accounted for. Intuitively, the URANS simulations are more accurate and therefore the efficiency calculated with them would be below the one estimated with less accurate methods. In this case, however, the results are counterintuitive. This is because the unsteady effects, that were unaccounted for in the RANS simulations, have a positive contribution on the overall aerodynamics of the machinery. Moreover, the unsteady effects tend to fall into the same periodic pattern, leading to a smooth oscillation of the momentum coefficient.



a) b)

Fig. 10 Streamlines for 90 degrees, $\lambda = 3$:a) RANS;b)URANS;

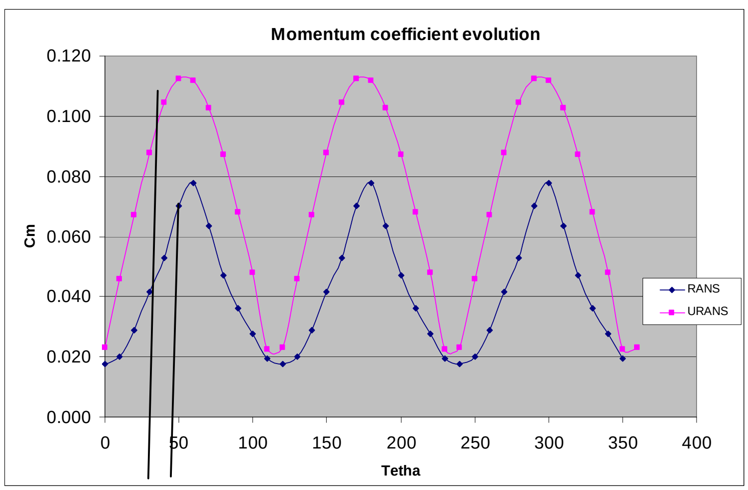


Fig. 11 Momentum coefficient variation, $\lambda = 3$

Fig. 11 presents the superimposed RANS and URANS momentum coefficient for various angular positions. A change in the maximum value of Cm by ~38% can easily be observed. Also, a slight increase in the minimal value and a shift in the oscillation phase may be noted.

For comparison, the overall performance of the machinery has been calculated using the classical analytical, RANS and URANS models. The results are synthesized in Table 1.

Table 1

The comparison between the analytical, RANS and URANS methods

Case / Results	RANS	Theory[10]	URANS
P_T[W]	120.5783	340	157.3345
C_{pT}	0.1055	0.3	0.1376

4. Conclusions and perspectives

The paper compared the RANS and URANS simulation techniques on a Darrieus vertical axis wind turbine case-study. This case was chosen for several reasons, firstly the Darrieus VAWT is one of the most important renewable energy power plants and is therefore significant for the current technological vision. Secondly, due to its operation, the Darrieus turbine has a significant percentage of unsteady phenomena – which can be easily quantified by URANS simulations.

The goal of the simulations was to estimate the efficiency of this lift-based turbine and also the evolution in time of the momentum coefficient Cm.

The turbine model was comprised of two domain, an interior rotating domain which contained the turbine blades and a secondary “far-field” domain which was stationary. The diameter of the stationary domain was calculated to be large enough so that the eddies generated by the turbine surfaces will dissipate before reaching the outer boundary.

For the RANS assessment, a number of 36 individual angular positions were tested at 10º increments, covering the 360º of a full rotation. In each position the flow parameters were evaluated and plotted.

In the unsteady URANS simulation, a “moving mesh” was set. The boundary conditions were such that the circumferential velocity matched one cell length per time step. The momentum coefficient was also used to check the case convergence.

Results of the RANS simulations underestimated the efficiency of the turbine in comparison to the URANS case. This is counterintuitive since, the expectancy was that the blade-vortex interaction (which can only be accurately predicted by the URANS simulation) will lead to detrimental effects.

It is therefore the main conclusion of this study that accurate CFD calculations on lift-based, Darrieus vertical axis wind turbines can only be made using time-dependent solvers and unsteady turbulence modeling.

The study also shows that steady RANS simulations can only give a qualitative explanation for the momentum coefficient variation with angular position. However, without accounting for the unsteady physical phenomena specific to this type of turbine, the steady calculation results underestimate the momentum coefficient and ultimately the overall turbine efficiency.

Finally, each of the two CFD methods has its advantages and downsides, depending on the design stage of the turbine. That is to say, in the preliminary phases, steady RANS simulations are to be preferred since they give fairly accurate qualitative results and are less time and resource demanding. However, for the final design stages, time-dependent URANS methods should be used in order to correctly asses the blade-vortex interactions and accurately determine the quantitative aspects of the turbine performance.

R E F E R EN C E S

[1] United States Patent US1835018

[2] *Paraschivoiu I.,Saeed F., Desobry V.* ”Prediction capabilitis in vertical axis wind turbine aerodynamics” Berlin, Germany 2002

[3] *Paraschivoiu I.*, „Double – Multiple Streamtube model for Darrieus wind turbine ”, Institute de recherche d’Hydro-Quebec, Canada.

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

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

[6] *Danao L.A., Qin N., Howell R.* „A numerical study of blade thickness and camber effects on VAWT” Proceedings of the Institution of Mechanical Engineers, Journal of Power and Energy,31 july 2012.

[7] *Ferreira S., Bijl H., G. Van Bussel,G van Kuik* „Simulating dynamic stall in a 2D VAWT”, Journal of Physics ,Conferance Series 75,2007

[8] *Wang S.,Tao Z.,* „Numerical investigation on dynamic stall associated with low Reynolds number flows over airfoils” 2nd International Conferance on Computer Engineering and Technology,2010.

[9] *Ionescu M.D. , Haraguta C., Ignat M., Silivestru V., Petcu R., Fetea G.* „Turbine eoliene cu ax vetical – contributii romanesti”, Ed Graph Byte,2012 ISBN 978-606-92852-9-9

[10] *Dumitrescu H., Cardos V.,Dumitrache Al.,* „Aerodinamica turbinelor de vant”, Ed Academiei Romane, 2001, ISBN 973-27-0849-2

[11] W.L.Oberbampf, T.G.Trucano, "Validation methodoloigy in Computational Fluid Dynamics", AIAA 2000-2549

[12] *Menter, F.R.* „Zonal two-equation k-ω turbulence model for aerodynamic flows”, AIAA Paper 1993-2906, 1993.

[13] Ansys – Fluent, User guide ,2013.

[14] *J. Wilcox*. "A Kinetic Investigation of High-Temperature Mercury Oxidation by Chlorine". Journal of Physical Chemistry A,. 113(24). 6633–6639. 2009.

[15] B. E. Launder and D. B. Spalding. Lectures in Mathematical Models of Turbulence. Academic Press, London, England. 1972.*Michael R. Mendenhall, Robert E. Childs, Joseph H. Morrison*, "Best practices for reduction of uncertainty in CFD results", American Institute of Aeronautics and Astronautics

[16] Fluent tutorial no.5, "Modeling compresible flow over an airfoil", Fluent Inc. 2007

[17] *Michael R. Mendenhall, Robert E. Childs, Joseph H. Morrison*, "Best practices for reduction of uncertainty in CFD results", American Institute of Aeronautics and Astronautics

[18] *M.F.White*, "Fluid mechanics", pag. 467, Ed. McGraw-hill, ISBN 9780072831801