Numerical Analysis of Exhaust Air Energy Extractor for Cooling Tower Applications

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Abstract. Over the years, the need of renewable energy has been accelerated to minimise the reliance on using the fast depleting fossil fuel. Research on wind turbines to harness wind power is widely increasing especially with the progression of vertical axis wind turbines (VAWT) for the locations, where conventional horizontal axis wind turbines are not effective. The ability to provide renewable energy by generating efficient power is vital in combatting climate change due to increase in global energy demand thus, leading to this present study of extracting wind energy from a cooling tower. In this paper, a three dimensional numerical investigation has been conducted on the straight bladed Darrieus type VAWTs with S1046 airfoils. The implicit unsteady Reynolds-Averaged Navier-Stokes equations are solved using shear stress transport k-ω turbulent model. The VAWT model is placed at the outlet of the cooling tower to calculate power output with an aspect ratio of 0.88. The results show that a maximum power coefficient of 0.36 is obtained at a tip speed ratio of 3.0.

1. Introduction
Increase in population density with rapid commercial and social development have been causing the need of increasing energy generation to meet the ever-growing energy demand. Fossil fuels, a form of non-renewable energy is still largely the source of energy today and is expected to remain contributing 84% of the total energy demand in 2030 [1] as it provides cheaper and more reliable energy solution. Too much dependency on this carbon-based fossil fuel sources leads to high emission of carbon gases to the atmosphere, hence causing the global warming issues. The fossil fuel combustion which emits carbon dioxide (CO₂) excessively to the environment with 2012 recording 32.3 billion metric tons of CO₂ emission and is expected to continue rising reaching 43.2 billion metric tons by 2040 [2]. Moreover, if this growing energy demand continues to be met by fossil fuel at the current rate, chances for the fossil fuel resource to deplete completely in a shorter amount of time is high. Policies and global climate deal such as The Paris Agreement 2015, bringing all nations together for a common cause to keep the global rise in temperature capped at 2°C and further reduce it to 1.5°C in the future by constant effort in reducing greenhouse gases emissions with developed countries providing aid to share the burden with developing countries [3]. Thus, production of cleaner and sustainable energy sources has become increasingly crucial and need continuous focus to explore different alternative solutions. The available resources from International Renewable Energy Agency showed that there has been continuous increase in renewable energy capacity growth over the last 5 years [4]. However, it is still not enough to supply
most of the increasing energy demand as the rate of growth is not fast enough to offset the effect of worldwide growing population and techno-economic and social needs.

In the above aspect, wind turbines are fund to be one of the most promising sources of renewable and sustainable energy generation, in large, medium, or small-scale applications [5]. Based on the axis of rotation, these wind turbines are classified into two broad categories, horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT). Many years of research and development focused on the HAWTs allowed possibility to widely utilize it for efficient commercial electricity generation in open field area with steady winds [6]. However, the rise in electricity needs and limited land space due to urbanization has directed more research to be done on the VAWTs to provide better solution to harness wind energy in areas where the HAWT is not suitable to be used. Advantages of VAWTs include simple design, low cut-in speed, lower noise level, adaptability to turbulent flows, flexibility of application in urban areas and its ease of maintenance. Being omnidirectional, i.e. capturing wind from any direction without yawing mechanism are added factor that give rise to research interest in this concept of wind turbines [7-8]. Based on the dominating aerodynamic forces, VAWTs can be further classified into lift type Darrieus wind turbines and drag type Savonius wind turbines [9]. Over the years, the evolution of the Darrieus wind turbines has led to two existing used designs: the curved eggbeater and the straight bladed H-rotor type. The better advantages of H-Darrieus turbines over its counterpart include a higher power coefficient and wider application capability that resulted it to be further researched and modified into designs such as fixed-pitch H-rotor, helical H-rotor, tilted H-rotor and also combined with Savonius type rotor [8]. The VAWTs are progressively being used in rural and urban areas to generate electricity to lessen the reliance on fossil fuel as an effort to battle climate issues. Ability to adapt to urban wind environment and being smaller in size allows the VAWTs to be installed at places such as on top of tall buildings, road side dividers, railway tracks and on top of lamp posts for local electricity generation [8]. However, locations with low speed wind conditions are unable to utilize the conventional way of wind power generation. An alternative approach of extracting power can be done by harnessing unnatural or artificial wind sources, such as exhaust air system of the cooling tower, at a consistent speed of about 5m/s to 16m/s [10] depending on the type and sizes of the cooling tower. Both atmospheric and mechanical induced cooling tower are used worldwide to remove heat waste from applications such as in thermal power plants, nuclear plants, oil refineries, chemical plants and heating, ventilation and air conditioning (HVAC) systems to cool buildings. The availability of these accelerated wind source through the cooling tower outlet for energy generation using wind turbines set off a new prospect to continue increasing the wind energy contribution in global renewable energy mix. Studies expanding the scope of VAWTs is actively ongoing, and one interesting study on the prospect of generating clean energy by extracting wind energy coming out from the exhaust outlet of a cooling tower has been proposed by Chong et al. [11]. However, the reported VAWTs struggled with poor efficiency in converting wind energy to useful electrical energy forcing continuous effort to study and experiment the different parameters of turbines with diffuser plates and guide vanes through experimental and numerical analysis [11-15].

Till last two decades, the straight-bladed H-Darrieus wind turbines (HDTW) with its simple design, construction and manufacturing appealed many authors to do experiment on its geometric features in effort to optimize and improve the characteristics, producing the best performance out of this turbine. However, the application these turbines for exhaust air-energy extraction is very much limited to few studies. So, the present study is focused on a three-dimensional modelling of a wind energy extractor system by placing the HDWT at the outlet of a cooling tower and hereby analyze its performance for this application.

2. Methodology

2.1. Key performance parameters
The key design parameters which are used in this study are tip speed ratio, aspect ratio, power coefficient, moment coefficient, as described below with the standard equations.
Tip speed ratio (TSR), is the ratio of blade tip translational speed \( u = \omega R \) to the wind velocity \( V_\infty \), where \( \omega \) and \( R \) is the angular velocity and radius of the turbine respectively.

\[
TSR = \frac{\omega R}{V_\infty}
\] (1)

Aspect ratio (AR) is the ratio of blade length \( H \) to the radius of the turbine \( R \), as expressed below:

\[
AR = \frac{H}{R}
\] (2)

Moment coefficient, \( C_m \) and power coefficient, \( C_p \) are the parameters of interest to measure the performance of turbines, which are a function of wind velocity, \( V_\infty \), mechanical torque, \( T \), output mechanical power, \( P \) and the turbine’s swept area, \( A \).

\[
Swept\ area, A = H \times D
\] (3)

\[
C_m = \frac{2T}{\rho A R V_\infty^2}
\] (4)

\[
C_p = \frac{P_{\text{turbine}}}{P_{\text{available}}} = \frac{2P}{\rho A V_\infty^3} = C_m \times TSR
\] (5)

2.2. Cooling tower and turbine parameters
A proper dimensioning of the cooling tower is needed as a computational domain for the simulation to replicate the air flowing out of the tower’s outlet as close as possible. Actual cooling tower parameters which was scaled down by factor of 200 used in a study by Liu et al. [16] was adapted in the present study. The parameters and dimensions of the cooling tower used as the shape of the computational domain are shown in figure 1 and table 1, respectively. The turbine selected for this study is a 3-bladed HDWT with S1046 airfoil with a turbine diameter of 456 mm and chord length of 45.6 mm. The aspect ratio is calculated as 0.88.

\[\text{Table 1. Cooling tower dimensions.}\]

| Parameter                  | Symbol | Dimension (mm) |
|---------------------------|--------|----------------|
| Tower height              | \( H_t \) | 1175 mm        |
| Base diameter of tower    | \( D_b \) | 910 mm         |
| Outlet diameter of tower  | \( D_o \) | 570 mm         |
| Throat diameter of tower  | \( D_{tt} \) | 525 mm        |
| Height of throat from base| \( H_{tt} \) | 881 mm        |

\[\text{Figure 1. Cooling tower parameters.}\]
2.3. Computational domain & boundary conditions

The computational domain is shown in figure 2. The domain and HDWT is designed in a computer-aided design (CAD) software, Solidworks and imported into Star CCM+. The domain is divided into two regions, a rotating region consists of HDWT and a stationary region. The stationary region consists two control volume, a cooling tower control volume, and a cuboidal outer domain. The centre of HDWT is placed at \(0.5D\) (\(D\) is the diameter of the turbine) from the cooling tower outlet at downstream. Cooling tower domain dimensions was set as mentioned in section 2.2 while the cuboidal domain dimensions were created large enough to avoid wall blockage and reverse flow effect as shown in figures 2 and 3.

![Figure 2. Computational domain](image)

![Figure 3. Turbine rotating computational domain](image)

2.4. Meshing topology

In this study, polyhedral mesh is generated with boundary layers applied to the blade surface with growth rate of 1.1, and thickness of 3mm to achieve wall \(Y^+\) value close to 1, as shown in figures 4 and 5.

![Figure 4. Three-dimensional computational domain.](image)
2.5. Physics conditions

In this numerical study, three-dimensional implicit unsteady Reynolds-Averaged Navier-Stokes (URANS) equations were solved with shear stress transport (SST) k-ω turbulent model solver. The air density and dynamic viscosity was set constant at 1.18415 kg/m$^3$ and 1.85508 x 10$^{-5}$ Pa.s respectively. Figure 5 illustrates the acceleration of the wind due to the converging cooling tower shape will result in higher wind speed at the outlet so, a inlet wind speed of 3.7 m/s was set such that the velocity obtained at the outlet of the cooling tower would be 9 m/s. Rotational speeds in the range of 47.37 rad/s – 421.05 rad/s were assigned to obtain TSRs in the range of 1.5 to 3.5. The time step was set to get azimuthal rotation increment of 5° which is acceptable for this study due to computational time constraints.

![Figure 5. Sectional view of full domain](image1)

![Figure 6. Cooling tower domain.](image2)

2.6. Governing equations

The SST k-ω model shows satisfactory efficiency and accuracy and has been used widely for turbulence modelling of VAWT. The mathematical formula associated with this turbulence model are as below:

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho U_i)}{\partial x_i} = 0$$  \hspace{1cm} (6)

Momentum equation:

$$\frac{\partial (\rho U_i)}{\partial t} + \frac{\partial (\rho U_i U_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial (\tau_{ij} - \rho U_i U_j)}{\partial x}$$  \hspace{1cm} (7)

Where, the viscous tensor is expressed as:

$$\tau_{ij} = \mu \left( \frac{\partial U_j}{\partial x_i} + \frac{\partial U_i}{\partial x_j} - \frac{2}{3} \delta_{ij} \frac{\partial U_l}{\partial x_l} \right)$$  \hspace{1cm} (8)
Transport equation for turbulent kinetic energy (k):
\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho \vec{u}_i k)}{\partial x_i} = P_k + D_k + \frac{\partial}{\partial x_i} \left[ (\mu + \sigma_k \mu_t) \frac{\partial k}{\partial x_i} \right]
\]
(9)

Specific dissipation rate (\(\omega\)):
\[
\frac{\partial (\rho \omega)}{\partial t} + \frac{\partial (\rho \vec{u}_i \omega)}{\partial x_i} = P_\omega + D_\omega + \frac{\partial}{\partial x_i} \left[ (\mu + \sigma_\omega \mu_t) \frac{\partial \omega}{\partial x_i} \right]
\]
(10)

Where production terms are:
\[
P_k = \mu_t \vec{S}^2 - \frac{2}{3} \rho k \frac{\partial (\vec{u}_i)}{\partial x_i} - \frac{2}{3} \mu_t \left( \frac{\partial (\vec{u}_i)}{\partial x_i} \right)^2
\]
(11)
\[
P_\omega = \rho \gamma \vec{S}^2 - \frac{2}{3} \rho \gamma \omega \frac{\partial (\vec{u}_i)}{\partial x_i} - \frac{2}{3} \rho \gamma \left( \frac{\partial (\vec{u}_i)}{\partial x_i} \right)^2
\]
(12)

Where the term:
\[
\vec{S}_{ij} = \frac{1}{2} \left( \frac{\partial \vec{u}_i}{\partial x_j} + \frac{\partial \vec{u}_j}{\partial x_i} \right)
\]
(13)

Destruction terms:
\[
D_k = -\rho \beta^* k \omega
\]
(14)
\[
D_\omega = -\rho \beta \omega^2
\]
(15)

Model coefficients are, \(\sigma_k\), \(\sigma_\omega\), \(\beta^*\) and \(\beta\), and \(\mu\) is the dynamic viscosity of the fluid.

3. Model Validation

Accuracy of CFD simulations depends on a few factors and one of it is the quality of the grid. To accurately generate a 3D mesh for URANS simulation, two grid independence tests were conducted, one with only the cooling tower and cuboidal control volume with wake-refinement at the center stretching from the cooling tower outlet up to the pressure outlet were meshed, and second, with the turbine placed at the outlet of the cooling tower as described previously and refinement around the HDWT rotating domain and blade domain. Lastly, the final computational grid was validated using NACA 0021 VAWT against previous experimental and numerical results. The results from second grid convergence study (with turbine case) is shown in figure 7. Finally, 5.6 million cells were considered where the accuracy is assured with the difference in \(C_m\) value is less than 1% from the subsequent value.

**Figure 7.** Grid independence study.
For validation, a three bladed NACA 0021 turbine with parameters shown in table 2 are used from the experimental data of Castelli [29] and simulation result from Hashem and Mohammed [23]. Figure 8 shows a good agreement of present numerical study to that of literature to allow the use of further study using this computational grid.

### Table 2. Validation parameters.

| Physics setup          | Values |
|------------------------|--------|
| Airfoil profile        | NACA 0021 |
| Inlet wind speed ($V_{in}$) | 9.00 m/s |
| Turbine diameter ($D$)  | 0.515 m  |
| Turbine span ($H$)      | 0.200 m  |
| Solidity ratio ($\sigma$) | 0.25     |
| Tip speed ratio (TSR)   | 1.44 - 3.0 |

**Figure 8.** Computational model validation

4. Results and Discussion

Following the development of computational model and validation, a series of numerical simulations were conducted with three-bladed HDWT using S-1046 airfoils for the blades. In this paper, the simulation results using aspect ratio of 0.88 has been reported at TSR in the range of 1.5 to 4.0. Figures 9 and 10 shows the moment coefficient and power coefficient plots for the mentioned HDWT model, placed at half the diameter of turbine from the outlet of the cooling tower.

**Figure 9.** Moment coefficient around HDWT

**Figure 10.** Power coefficient around HDWT

From the obtained results of moment coefficient, the power coefficient values are calculated by multiplying with the respective TSR values. It has been observed at TSR of 3.0, the maximum power coefficient is 0.36 for the tested model of HDWT. Further, for the complete turbine rotations, the instantaneous moments and power coefficients are analyzed with respect to 15-degree interval of azimuthal angle, as shown in Figures 11 and 12. Velocity contour of the air flow for the turbine at chosen critical azimuthal angles of 0=30°, 60°, 90° and 120° at low TSR of 2.0 and high TSR of 3.5 are shown.
in figure 13 and 14 respectively to analyse the flow characteristics and compare the difference in performance.

![Figure 11. Instantaneous coefficient of moment versus rotor blade azimuth angles at TSR 2.0, 2.5, 3.0 and 3.5.](image1)

![Figure 12. Instantaneous coefficient of power versus rotor blade azimuth angles at TSR 2.0, 2.5, 3.0 and 3.5.](image2)

The radar plot shows that the turbine has better moment coefficient at lower TSR of 2.0, 2.5 and 3.0 as it produce positive moment for a complete turbine rotation while at TSR of 3.5, it shows much lower moment coefficient with negative moment at some azimuth angles. Overall, TSR 3.0 gives highest power coefficient at most azimuth angles as seen in Figure 12.
There is presence of high wind velocity of 35 m/s to 50 m/s building up around the turbines. The turbine gave lowest $C_m$ at azimuth angles between 60° to 90° as flow separation of high wind velocity occurs at blades 1 and 3 as can be seen in figure 13. At azimuth position of 60°, higher wind velocity located at the lower part of blades 2 and 3 for both the 0.88 aspect ratio turbine results in lesser lift generation. At 120°, the high velocity difference between the top and bottom side of the leading-edge turbine blades produces high pressure difference with lower pressure region above the blades allowing greater lift generations for the turbines at this azimuth angle. Overall,
highest wind velocity regions are concentrated at the right side of the turbines as the air exiting the cooling tower is guided by the anticlockwise motion of the turbine towards the right side.

4.2 Velocity contour at high TSR=3.50. Figure 14 shows the minimal difference of pressure between top and bottom of the blades which obstructs lift generation for this high TSR turbine. The presence of wake regions from the blades at this TSR affects the performance slightly compared to lower TSR. This explains the negative moment generated at azimuth angles of 60° for the blades. The turbine still produces positive moment as it gives high difference in wind velocity of about 14-21 m/s between the top and bottom of blades 2 and 3 at positions 90° to 120° resulting in pressure difference which generates lift. The velocity contour as shown in figure 14 suggest the same comparison whereby TSR higher than 3.0 does not give any better performance compared to the lower TSR of 2.0, 2.5 and 3.0.

5. Conclusion
A computational analysis of wind turbine placed at cooling tower exhaust has been conducted using a straight-bladed H-Darrieus wind turbine (HDWT) with S1046 airfoil. With a turbine aspect ratio of 0.88, a maximum power coefficient of 0.36 is obtained at TSR 3.0. However, this is just a preliminary study focused on the computational mesh and model development for the three-bladed HDWT in a cooling tower application. The successful validation also signifies the outcome of the study. However, several studies being conducted on the aspect ratio and optimising the location of the turbine. The effect of guide vanes and diffusers to further improve the performance will also be investigated in future work.

Acknowledgement
The authors would like to thank Curtin University Malaysia for providing the facility, especially the Star CCM+ software license to carry out the numerical study. Sincere gratitude is also dedicated to Ministry of Higher Education (MOHE) Malaysia for the financial support by awarding the Fundamental Research Grant Scheme (FRGS Grant: FRGS/1/2018/TK10/CURTIN/03/1) to carry out this project.

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