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CFD Analysis of Operational Flow Nature of a Wind Turbine Model Using Environmental Wind Data from Nigerian Defence Academy (NDA)

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Abstract

A wind turbine is a machine which converts the power in the wind into electricity. It operates under varying wind speeds depending on the environmental wind conditions. In this paper, we have presented the operational flow analysis of a proposed wind turbine model in Nigerian Defence Academy (NDA) Kaduna. The case study is for 5.6m/s, 7.5m/s and 9.5m/s wind speed. The model design and assembly of the components were done with the help of SolidWorks 2018 and the operational flow analysis done with ANSYS 15.0. The result showed that the flow nature of the turbine model grew from laminar flow to turbulent flow increasingly with the environmental wind speed. The flow nature remained laminar from 0.0356 to 1780 Reynolds at 5.6m/s. At 7.5m/s wind speed, from laminar 0.403 Reynolds to turbulent 4290 Reynolds and at 9.5m/s, from laminar 0.381 Reynolds to turbulent 4900 Reynolds. High turbulent flow and mass imbalance nature depicts that phenomenon like wake and vibration of the system occurred.

Keywords: Wind speed, turbine, laminar flow, turbulent flow, mass imbalance

1.0 INTRODUCTION

A wind turbine is a machine which converts the wind power into electricity. It uses the aerodynamic force of the lift to rotate a shaft which in turn helps in the conversion of mechanical power to electricity by means of a generator. The primary application of wind turbines is to generate energy using the wind. Hence, the aerodynamics is a very important aspect of wind turbines [1]. Therefore, no doubt that energy has a major impact on every aspect of our socio-economic life. It plays a vital role in the economic, social and political development of our nation. The supply of electrical power from the national grid. Only about 40% of the nation's over 200 million has access to grid electricity, even though it is highly unreliable. There is, therefore, the need to harness renewable energy potential (such as wind, solar etc.) for reliable power supply in Nigeria [2].

Generating wind is described as a natural phenomenon related to the movement of air masses caused primarily by the differential solar heating of the earth's surface [3]. Wind speed in Nigeria is reported ranges from 1.4 to 5.0m/s in the southern areas and 5.12m/s above in the extreme north [4]. Wind speeds are generally weak in the southern part of the country except for the coastal regions and offshore location. The Nigerian Defence Academy (NDA) permanent site is located in Igabi Local Government Area of Kaduna state. The institution lies exactly between longitudes 7º 12'E to 7º 35'E of the Greenwich meridian and latitude 10º 36'N to 10º 42'N of the equator [5].

A wind turbine (WT) is composed of five main elements:

i. Rotor made up of rotor blades that use aerodynamic lift to convert wind energy into mechanical energy.

ii. A rotor bearing fixed on a structure that causes a defined rotation of the rotor and leads to conversion of the aerodynamic wind energy into a rotational shaft torque.

iii. A yaw system, which is a system that maintains the horizontal rotor axis pointing upstream into the wind.

iv. A power conversion system that converts the low-speed rotational energy into suitable shaft power to drive an electrical generator.

v. A tower and foundation structure to support the rotor and generator system at a height that harvests the most amount of energy for an acceptable capital cost.

vi. An electrical power distribution system that supplies the energy to the consumer in compliance with local grid code and system requirements.[6]

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Wind turbines produce some noise when they operate. Most of the turbine noise is masked by the sound of the wind itself, and the turbines run only when the wind operates in turbulent nature of the wind flow which might cause excessive noise and vibration of the turbine. Therefore, it is important to simulate a turbine model operational nature to ascertain that it can withstand a given environmental wind speed condition before its installation. This helps in taking care of the turbines' operational noise in the located environment.

blows. Proper siting and insulating materials can be used to minimize noise impacts [7, 8, 9]. But at most, turbine

There are many things to consider in designing wind turbine and its components, but most of them fall into one of two categories such as mechanical (structural) and aerodynamics considerations. This paper presents the aerodynamic analysis (flow nature) of a designed wind turbine generated by the environmental wind speed of Nigerian Defence Academy Afaka Kaduna.

Figure 1: A wind turbine model using SolidWorks 2018 and ANSYS 15.0 software.

2.0 MATERIAL AND METHOD

The study has been carried out in three parts. First was the mechanical and aerodynamic consideration of the components of a wind turbine. Followed by calculations of various parameters from the wind speed data obtained from NiMet using Excel spreadsheet (shown in the main work) and CAD model of a turbine developed in 3D modeling software such as SolidWorks 2018. Finally, the simulation of the modeled turbine using ANSYS. 15 software. In this paper, the operational flow nature of the designed wind turbine was analyzed.

The designed turbine was made by different types of component materials such as i.e., cast alloy steel as the base, chromium stainless steel as the bearing, aluminum 2024 T361 as the blade, copper as the rotor, cast alloy steel as the housing, alloy steel as the tower and shaft. Alloy steel have a good strength but it contributes more weight to the turbine and the methods are descripted using the figure 2 and 3 below.

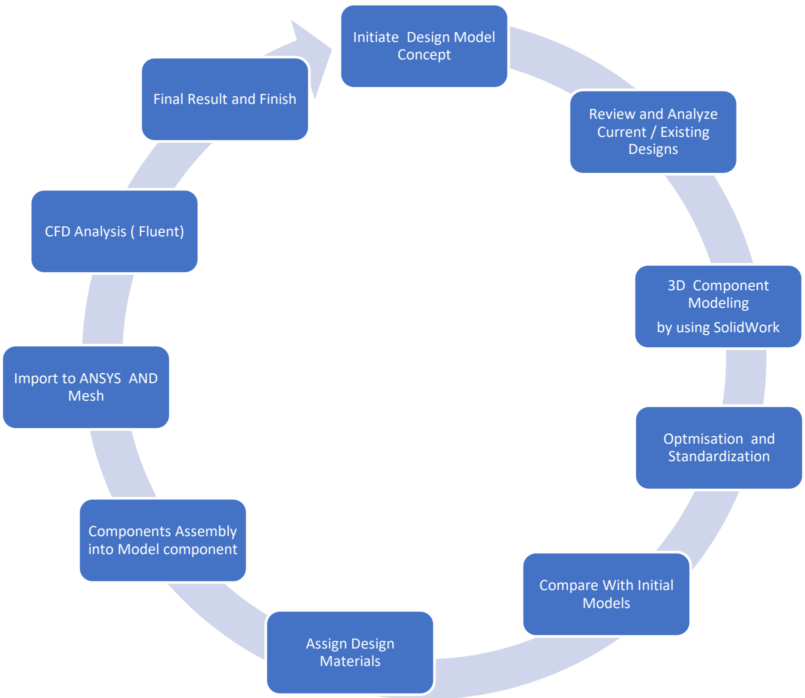

Figure 2: The Model Design and Simulation Process Flowchart

2.1 Meshing

Computer Aided Design (CAD) Model of a wind turbine component was produced in 3D modeling software such as SolidWorks 2018. This CAD model was imported into an ANSYS 15.0. In this case, it was not necessary to set a mesh control because these have default mesh control. Therefore, a smart mesh control was used to produce the fine mesh generation since the model geometry is complex.

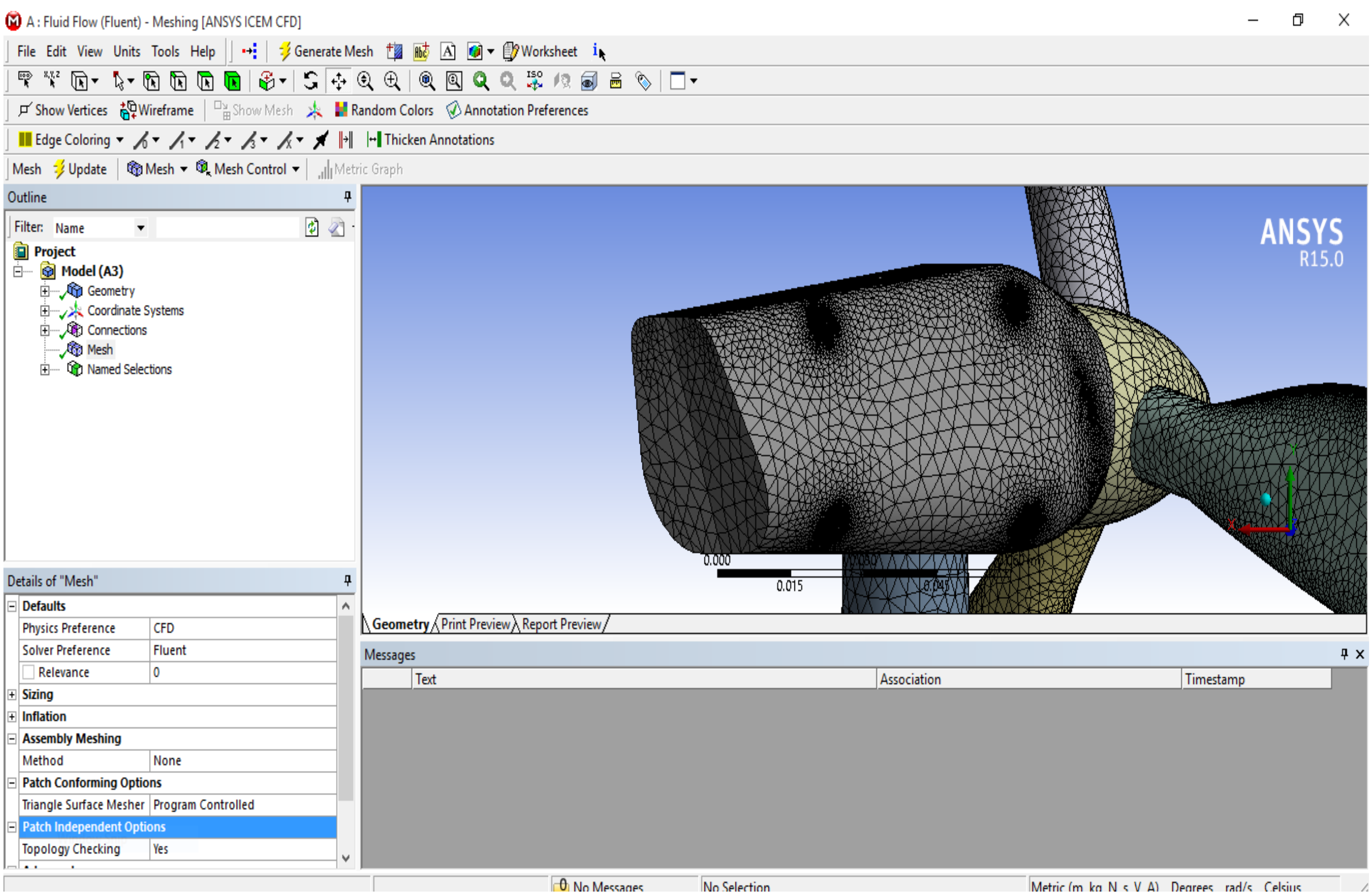

Figure 3: The Model Meshing.

2.2 *Governing Equation*

The mathematical model selected for this work is the standard K-ε model which is one of the Reynolds Averaged Navies-Stoke (RANS) model available in fluent. The standard K-ε model is the most widely used transport model. The standard K-ε model is a two-equation model and the two model equations are as follows: The model equation for the turbulent kinetic energy K is:

$$\frac{DK}{Dt} = \frac{\partial K}{\partial t} + \mathrm{u}_j \frac{\partial K}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\frac{V_t}{\sigma_k}\frac{\partial K}{\partial x_j}\right] + P - \varepsilon \qquad (1)$$

Where, Rate of increase of K+ Convective transport= diffusive transport + Rate of production-Rate of destruction

The model equation for the turbulent dissipation ε is:

$$\frac{D\varepsilon}{Dt} = \frac{\partial K}{\partial t} + \mathrm{u}_j \frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\frac{V_t}{\sigma_k}\frac{\partial \varepsilon}{\partial x_j}\right] + C_{\varepsilon_1}\frac{P\varepsilon}{K} - C_{\varepsilon_2}\frac{\varepsilon^2}{K} \qquad (2)$$

Where, Rate of increase of ε+ Convective transport= diffusive transport + Rate of production-Rate of destruction. The standard values of all the model constants as fitted with benchmark experiments are.

$$C\mu = 0.09\,;\ \sigma k = 1.00\,;\ \sigma\varepsilon = 1.30\,;\ C\varepsilon_1 = 1.44\,;\ C\varepsilon_2 = 1.92$$

Now the Reynolds stresses are found out using:

$$-\rho\overline{u_i'u_j'} = \frac{2\rho}{3}K\delta_{ij} + \mu_t\left(\frac{\partial\overline{u_i}}{\partial x_j} + \frac{\partial\overline{u_j}}{\partial x_i}\right) \qquad (3)$$

And the eddy-viscosity is evaluated as:

$$\mu_t = C_\mu\frac{K^2}{\varepsilon} \qquad (4)$$

The major advantages of this model are that it is relatively simple to implement, it leads to stable calculations, and it is a widely validated turbulence model. The known limitation of this model is that its performance is very poor for flows with strong separation tendency, large streamline curvature and high swirling components. Despite of all these limitations, the model is widely accepted for initial level screening of alternate designs in compressible flows, combustion engineering etc.

2.3. Boundary Conditions and Initialization.

The geometry of the turbine was divided into two zones and the zones included the inlet and outlet. The turbine front blades surfaces were designated as inlet to the direction of air flow. the boundary conditions given as the flow density 1.18 kg/m^3 velocities 5.6 m/s, 7.5 m/s and 9.5 m/s which were the environmental wind data of NDA and the outlet defined as behind the turbine walls. With all the zones properly defined, the model solution process was initialized and simulated for 50 calculation iterations on FLUENT solver. The solver was used based on the conditions that the design turbine geometry is energy equation K-epsilon model. The material is a steady fluid flow (Air). When the solution process is complete without errors or warnings, the solver notifies the user and results were displayed

3.0 RESULTS AND DISCUSSIONS

The flow nature analysis of wind turbine component is done in ANSYS 15.0. The operational mass imbalance of the system, laminar, turbulent flow nature was determined from various wind speeds of NDA environ. (wind speed data obtained from NiMet.).

Case I. Wind Velocity 9.5m/s

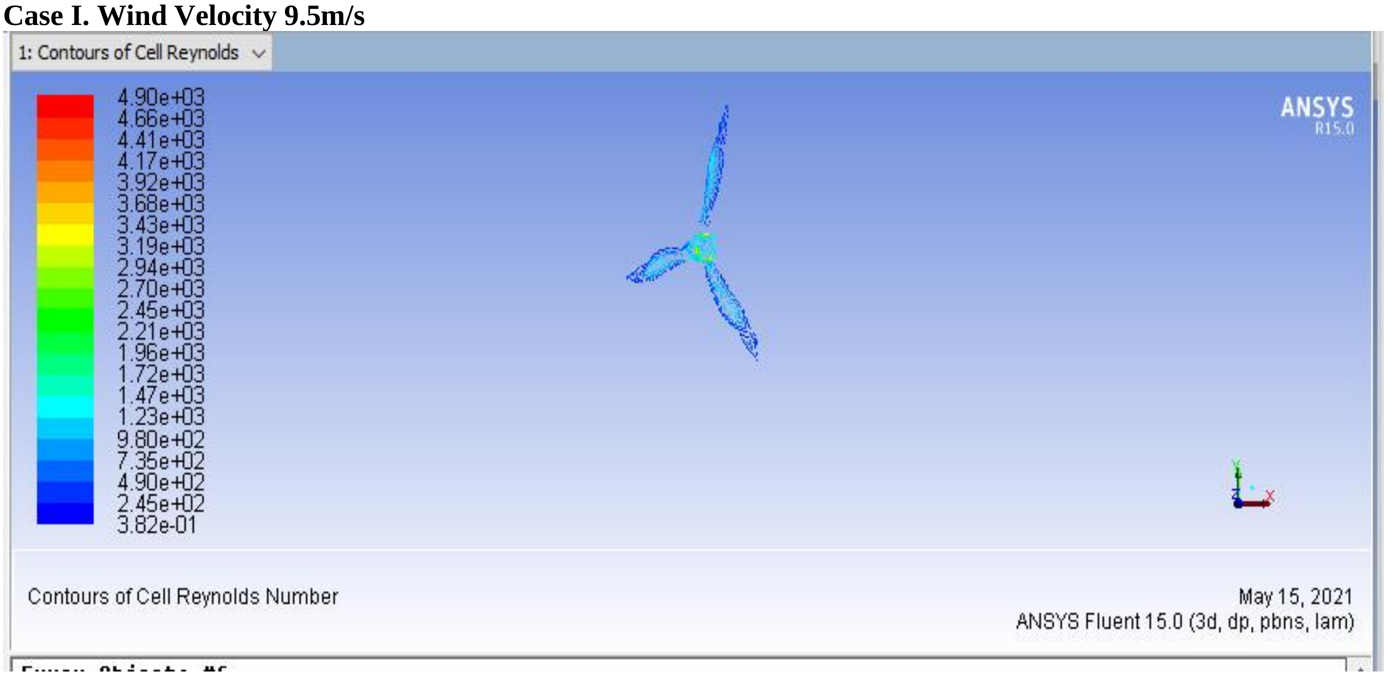

Figure 4: The flow Reynolds number of the Turbine in Operation.

The variation of mass imbalance and Reynolds number predicts the flow nature and effects (whether it is bound to vibration or not) on the systems. Thus, the flow results are shown in the figures 4,5,6,7,8 and 9 respectively.

From the Reynolds number above (figure 4). The flow grew from 3.82e-01 laminar within the feed speed of 9.5m/s as shown as the variation blue colours and into turbulent at 2.21e+03 shown as the variation green to red. It can be seen that the turbulent flow highest value at 4.90e+03 (red) Also, from the mass imbalance (figure 5). During the operation of the system, there is variation of mass imbalance from -4.92e-07 which is the minimum value to the maximum value of 8.71e-0.7. high turbulent flow and mass imbalance nature depicts that phenomenon like wake and vibration of the system occurred.

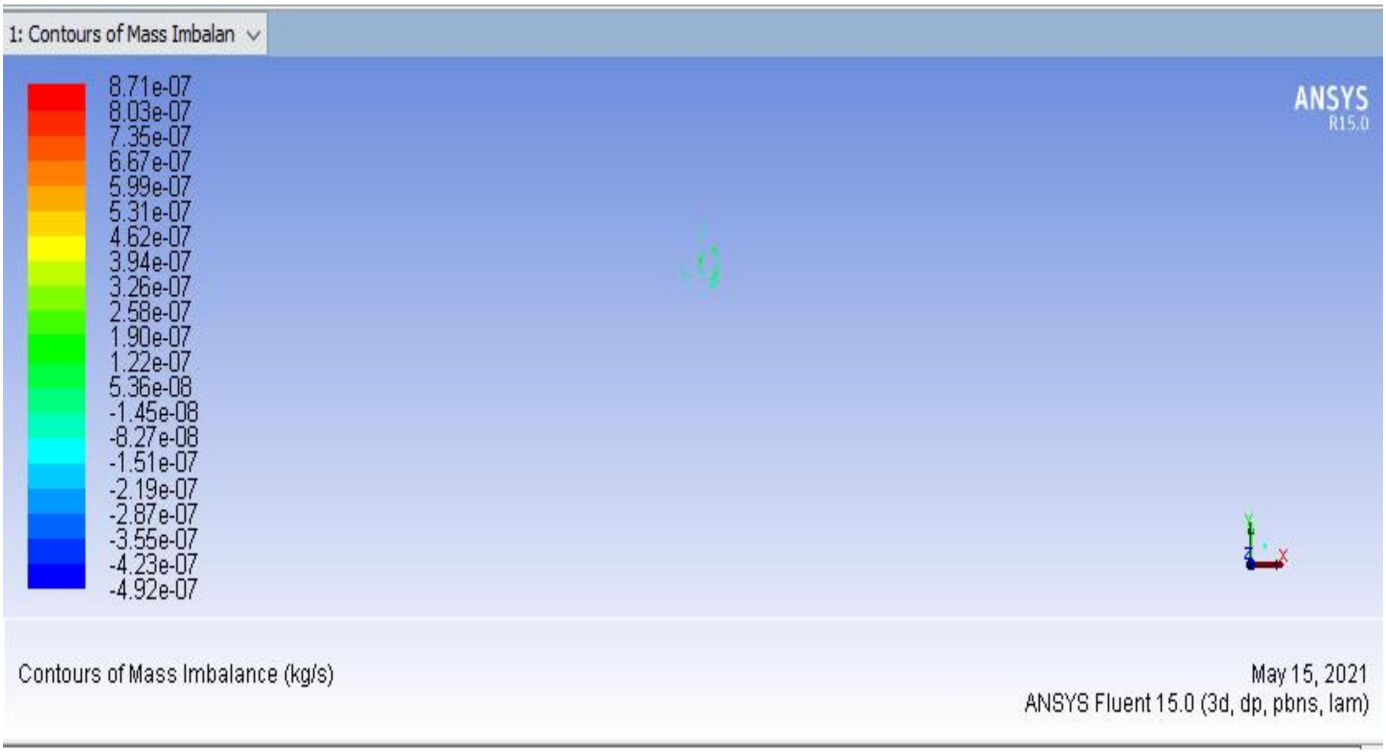

Figure 5: The flow Mass Imbalance of the Turbine in Operation.

Case II. Wind Velocity 7.5m/s

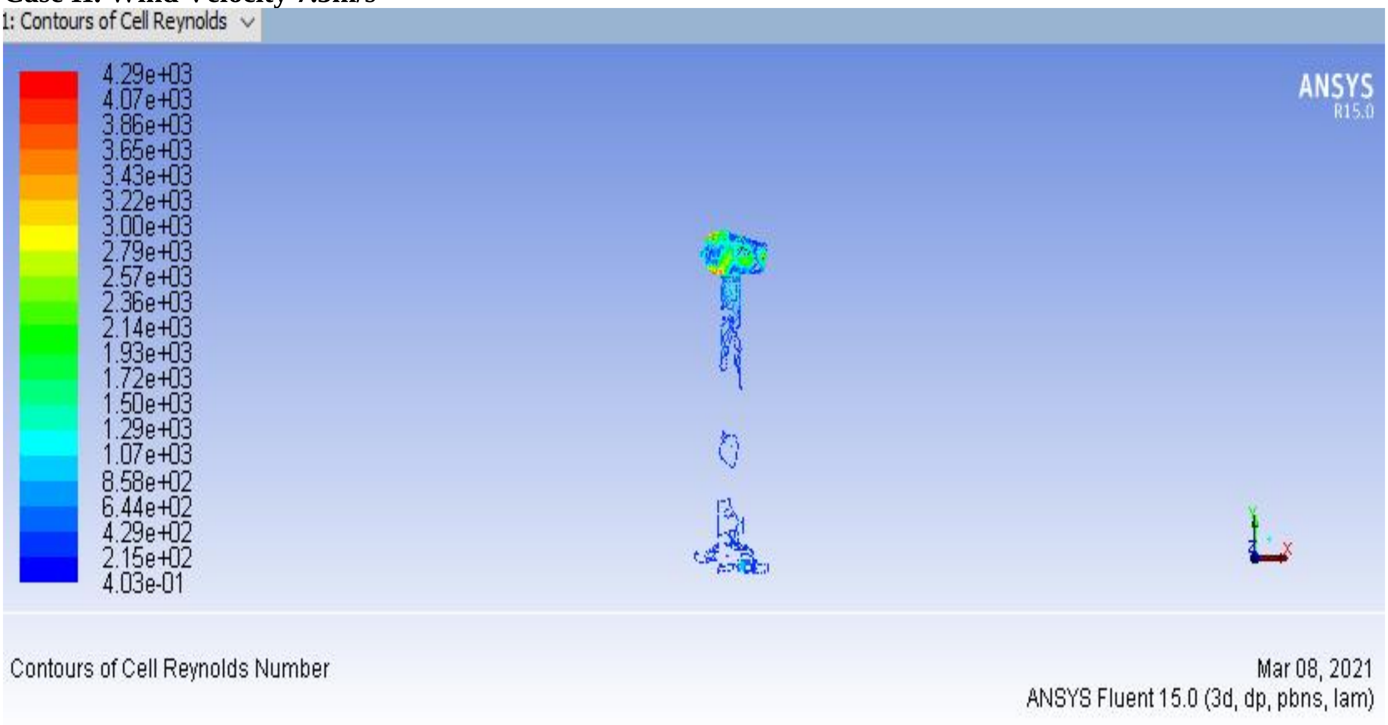

Figure 6: The flow Reynolds number of the Turbine in Operation.

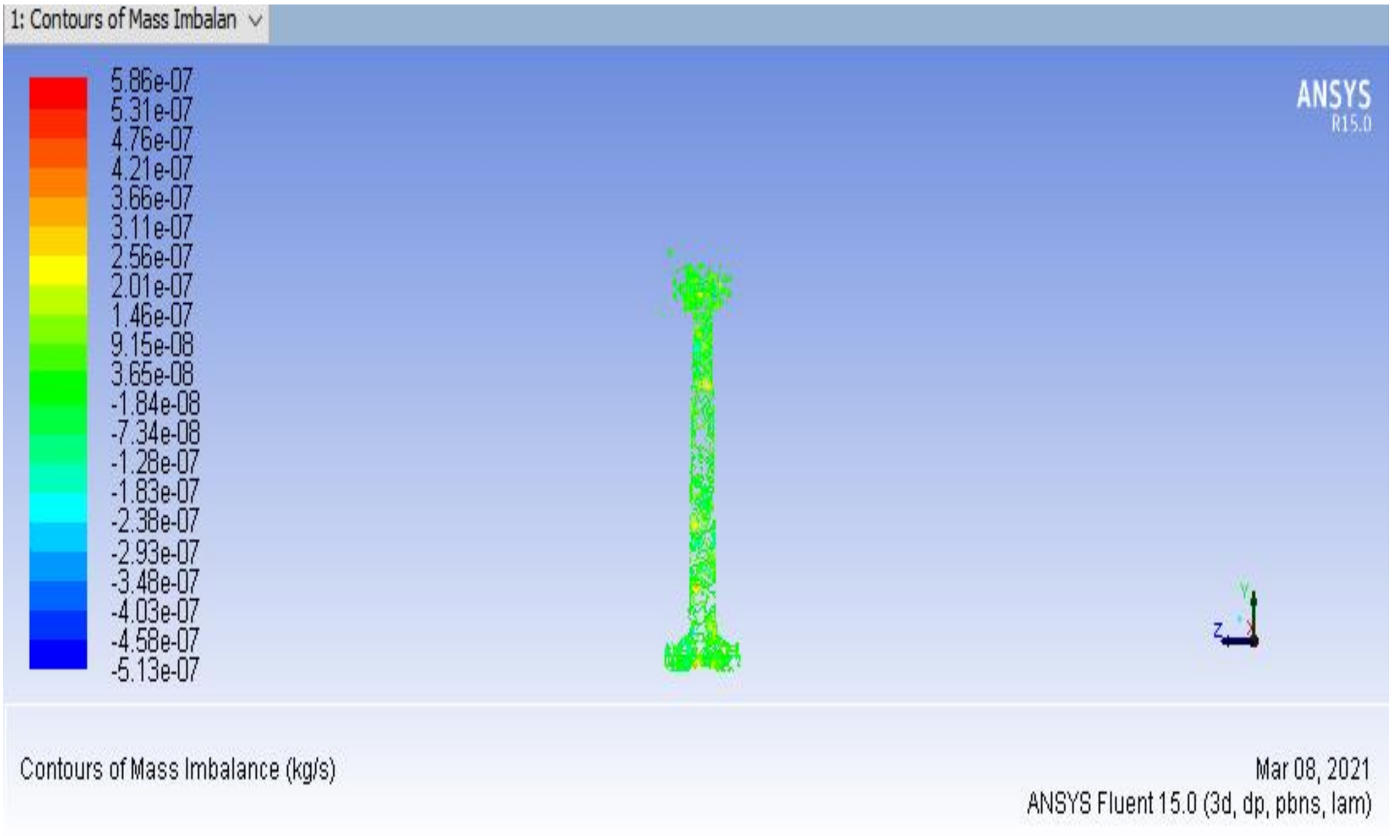

Figure 7: The flow Mass Imbalance of the Turbine in Operation.

From the Reynolds number above (figure 6). The flow grew from 4.03e-01 laminar within the feed speed of 7.5m/s as shown as the variation blue colours and into turbulent at 2.14e+03 shown as the variation green to red. It can be seen that the turbulent flow highest value at 4.29e+03 (red) Also, from the mass imbalance (figure 7).

During the operation of the system, there is variation of mass imbalance from -5.13e-07 which is the minimum value to the maximum value of 5.86e-0.7. high turbulent flow and mass imbalance nature depicts that phenomenon like wake and vibration of the system occurred.

Case III. Wind Velocity 5.6m/s

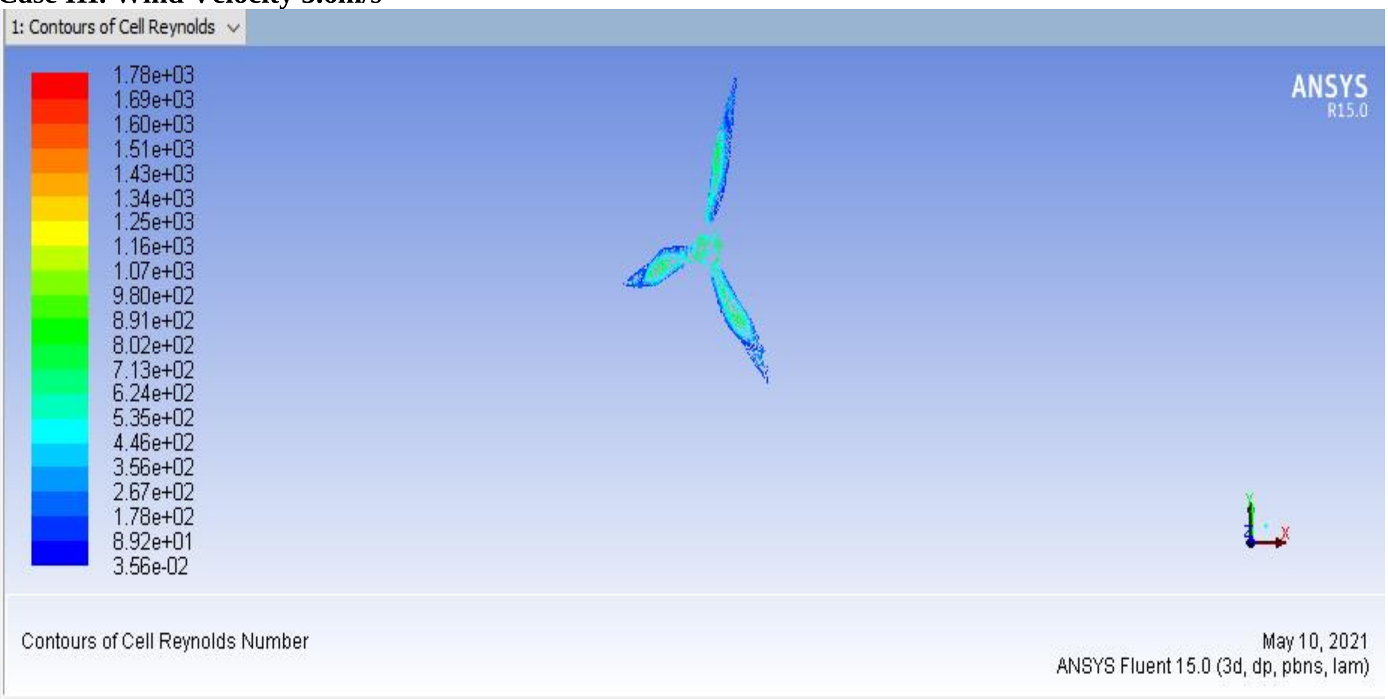

Figure 8: The flow Reynolds number of the Turbine in Operation.

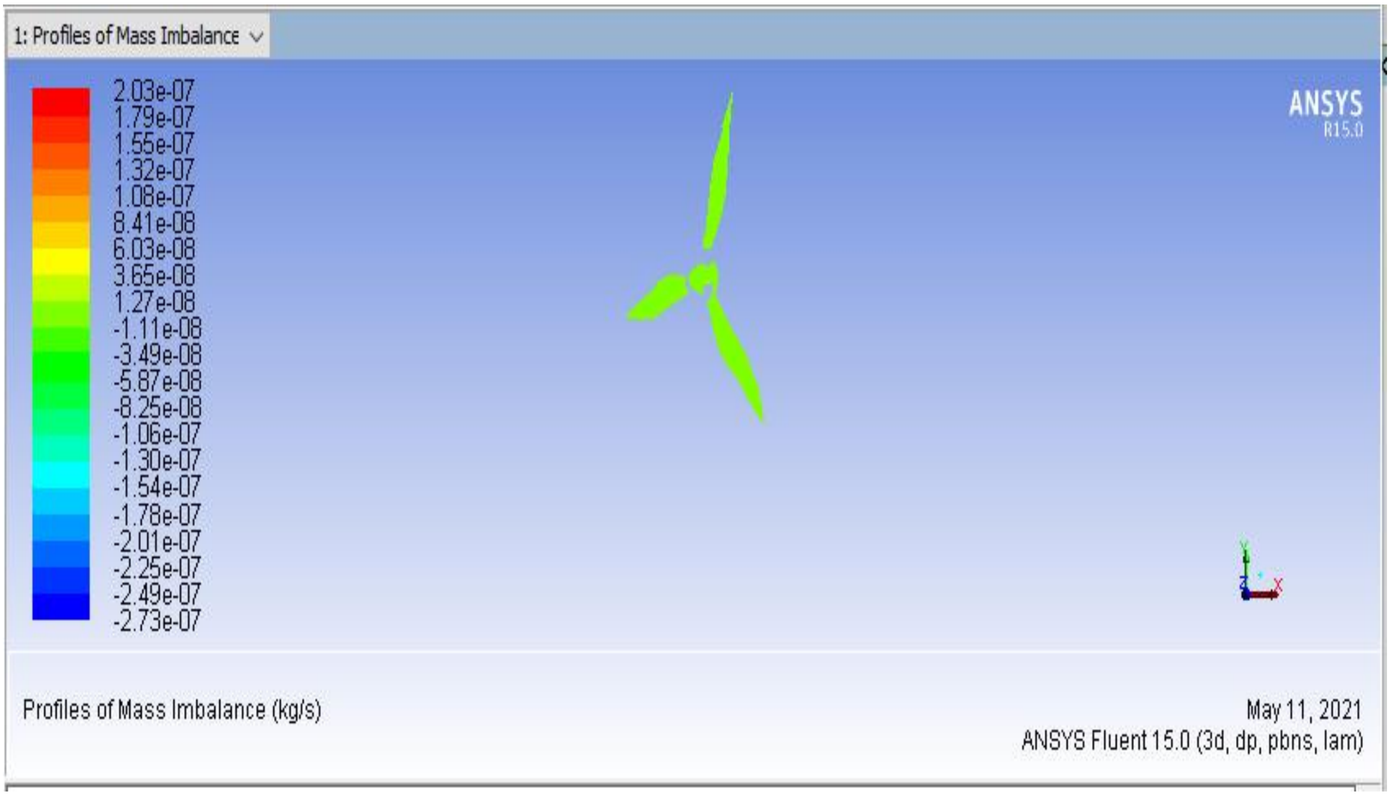

Figure 9: The flow Mass Imbalance of the Turbine in Operation.

From the Reynolds number above (figure 8). The flow remained laminar from 3.56e-02 within the feed speed of 5.6m/s as shown as the variation blue to red colours to highest value at 1.78e+03 (red) Also, from the mass imbalance (figure 9). During the operation of the system, there is variation of mass imbalance from -2.73e-07 which is the minimum value to the maximum value of 2.03e-0.7. high turbulent flow and mass imbalance nature depicts that phenomenon like wake and vibration of the system occurred. But the model operation flow here is not turbulent.

4. CONCLUSION

The wind turbine model has been modelled using SolidWorks 2018 and analyzed using ANSYS 15.0. The various flow characteristics such as, mass imbalance, laminar flow and turbulent flow are analyzed. The result showed that the flow nature of the turbine model grew from laminar flow to turbulent flow increasingly with the environmental wind speed. The flow nature remained laminar from 0.0356 to 1780 Reynolds at 5.6m/s. At 7.5m/s wind speed, from 0.403 laminar to turbulent 4290 Reynolds and at 9.5m/s, from 0.381 laminar to turbulent 4900 Reynolds. High turbulent flow and mass imbalance nature depicts that phenomenon like wake and vibration of the system occurred.

For future works, it is recommended that higher version of ANSYS solver and number of iteration calculation other than 50 be used for more accurate solution or another CFD simulation software for validation of the obtained results of the same model. (you can request for the CAD model through the email of any of the Authors).

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