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Thermal Analysis of Wind Turbine Nacelle using OpenFoam

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Abstract — Electricity generation using wind turbines is an uprising technology with advancements happening on a daily basis. Electricity is generated by conversion of kinetic energy of the wind into mechanical energy of rotation of the blades. The blades are connected to a series of power transmission, lubrication, hydraulic and braking system components which get heated up when the wind turbine is in continuous operation. The wind turbine is equipped with sensors which trigger down the wind turbine power when these components are overheated. This in turn reduces the power output given by the wind turbine. This paper involves the study of air flow and temperature distribution inside wind turbine nacelle and improvement opportunities for cooling of components inside nacelle. 3D CFD simulation is carried out using OpenFoam software which is a freeware. Three cases are constructed in OpenFoam and comparative study is done to find out improvement opportunities for cooling of the components.

Key words — Computational Fluid Dynamics (CFD), Coupling, Generator, Nacelle Cover, OpenFoam, Wind Turbine.

1. INTRODUCTION

Wind energy is one of the fastest growing renewable energy industries. Within the last decades this development has created a demand for increasingly accurate and efficient models for wind applications. Wind turbines of capacities ranging from 1MW-6MW are available for electricity generation. The capacity of wind turbine directly or indirectly depends on the cooling efficiency of the cooling systems provided for components inside wind turbine. Capacity of wind turbine can be increased if the components can work effectively without overheating for longer period of time. Thus, increasing the efficiency of cooling system of wind turbine plays a crucial part in development of wind turbine designs. Basic wind turbine components like rotor, gearbox, coupling and generator are considered in this study. These components are assembled inside a housing known as nacelle cover. Separate cooling systems are provided for gearbox and generator. The temperature inside nacelle cover is maintained with the help of two intake and two exhaust fans provided at the back and top of nacelle cover respectively. Gearbox, coupling and generator are identified as main heat sources. Scope of this study is to explore opportunities for improvement in cooling of coupling which is a power transmission component between gearbox and generator and gets heated due to continuous operation. Overheating of coupling triggers the sensors and wind turbine operates in reduced power mode to compensate for the excess increase in temperature of coupling. Three cases with different arrangements are constructed in OpenFoam software. Comparative study is done to find out best case for cooling of coupling. Salome software is used for pre-processing and ParaView software for post-processing.

2. WIND TURBINE COMPONENTS

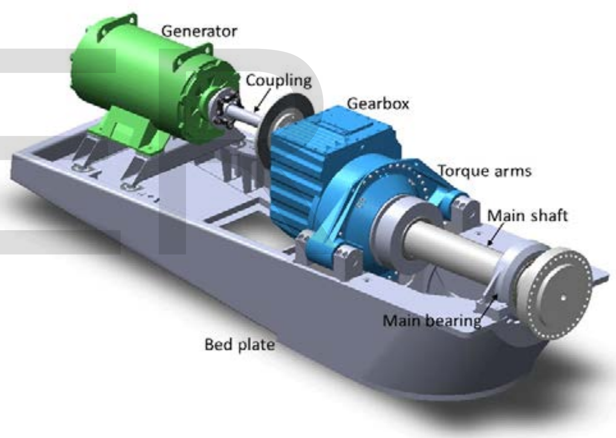

Fig. 1. Wind turbine components

Wind turbine blades are connected to the main shaft. It is made of high-grade heat-treated steel. To reduce weight without losing strength it is made hollow. The main shaft is connected to gearbox. Gearbox is typically used in a wind turbine to increase rotational speed from a low-speed rotor to a higher speed electrical generator. A common ratio is about 90:1, with a rate 20 rpm input from the rotor to 1,500 rpm output for the generator. Power transmission from gearbox to generator is done with the help of coupling. Mechanical couplings connect shafts so one can transmit rotational power to the other. The coupling incorporated onto a high-speed shaft also allows for a degree of misalignment. In wind turbines, flexible couplings are used on the high-speed (output) shaft of the gearbox to drive the generator and accommodate the misalignment between the two. Due to

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continuous rotation and friction these components get heated up and need to be cooled.

Fig. 2. Nacelle cover

The nacelle is the part of the turbine inside which are placed components that transform the wind's kinetic energy into mechanical energy to turn a generator that produces electricity. The nacelle looks impressive from a distance, installed on top of its tall steel or concrete tower, but get closer and you see that utility-scale machines are very massive. Their nacelles can stretch to over 50-ft long, and weigh up to 300 tons and more depending on the manufacturer and power rating.

Most nacelles have common components, such as a hub, rotor, gearbox, generator, inverters, hydraulics, and bearings. More than 1,500 small and large components and subsystems are housed in the nacelle and they are rarely obtained off-the-shelf.

2. CONJUGATE HEAT TRANSFER

If we consider heat transfer without any source terms or radiation, what is left are conduction and convection. Steady-state conduction of heat in solid is defined by the Fourier's Heat equation which is defined as $k.(\partial^2 T/\partial x_i^2) = 0$. This means that the heat conductivity k of the material is the only variables that affects the temperature field in the solid when the boundary conditions are fixed. On the other hand the equation that governs the transport of the heat in the flow field is known as the energy equation, which is defined as $\partial/\partial x_i (\rho u_i T) = \partial/\partial x_i ((k/C_p)(\partial u_j/\partial x_j))$ where T is the temperature, k is the conductivity, ρ the density and Cp the specific heat of the fluid. The ui is of course the velocity in each Cartesian directions i, j and k. When both the conduction in the solid and the convection in the fluid are computed together so that the temperature field obeys the laws of thermodynamics, it is called a conjugate heat transfer problem.

3. ASSUMPTIONS AND MATERIAL PROPERTIES

- Problem is solved for steady state.
- k-∈ RANS turbulence model is used.
- Fluid is assumed as air and solid components like gearbox, coupling and generator are assumed as steel in the simulations.

Table No. 1 Properties for fluid (Air)

molWeight (Molecular Weight) [kg/mol]	28.96
Cp (Specific Heat) [J/kg.K]	1004.5
mu (Dynamic viscosity) [kg/m.s]	1.8e-05
Pr (Prandtl number)	0.7

Table No. 2 Properties for solid (Steel)

molWeight (Molecular Weight) [kg/mol]	55
Cp (Specific Heat) [J/kg.K]	500
kappa (Thermal conductivity) [W/m.K]	50
rho (Density) [kg/m^3]	8000

4. CFD MODELLING AND BOUNDARY CONDITIONS

Fan Modelling:

The fans are modelled as flat disks with zero thickness and pressure jump boundary condition is applied on disks. The jump table for pressure jump boundary condition is calculated from the fan characteristic curves.

Heat Exchanger Modelling:

The heat exchanger is modelled as a flat disk and porosity is applied using pressure drop boundary condition by specifying Darcy & Forcheimer coefficients. The porous coefficient values are calculated by using the characteristic resistance curve of heat exchanger.

Heat Sources Modelling:

Generator, Coupling and Gearbox are modelled as heat sources.

There are two openings at bottom of nacelle. There are two openings at the back of nacelle and red arrows indicate the inlet direction of air. There are two openings at the top of nacelle and yellow arrows indicate the outlet direction of air.

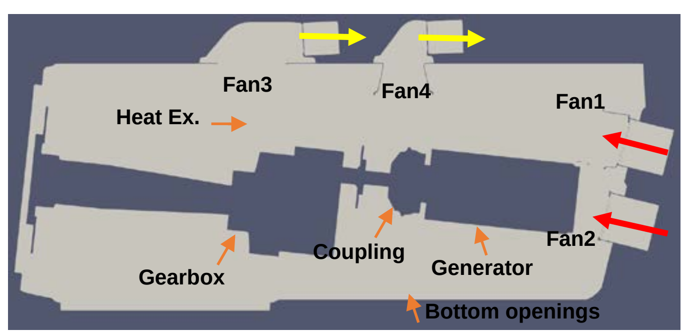

Fig. 3. Nomenclature and boundary conditions

There are two openings at bottom of nacelle. There are two openings at the back of nacelle and red arrows indicate the

inlet direction of air. There are two openings at the top of nacelle and yellow arrows indicate the outlet direction of air. Fans are located at all four openings for forced convection heat transfer. Fan1 and fan2 suck in air from back side of nacelle. Fan3 and fan4 throw out air from top side of nacelle. Heat losses from gearbox, coupling and generator are taken as 9KW, 36KW and 39KW respectively. Pressure jump boundary condition is applied for all fans and volumetric heat source boundary condition (W/m^3) is applied for all heat sources.

5. CFD ANALYSIS FOR THREE CASES

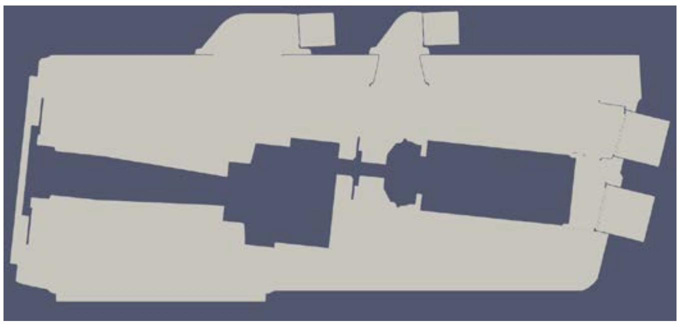

Fig. 4. Case I - Baseline Case

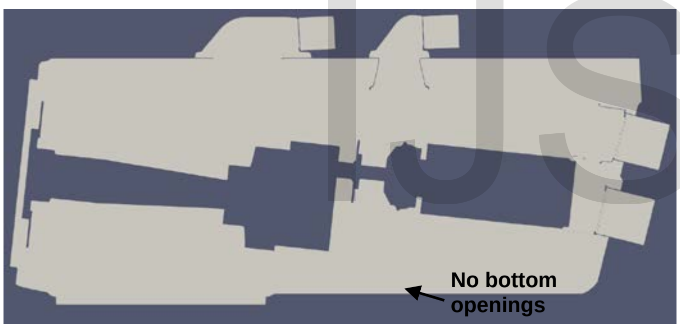

Fig. 5. Case II with no bottom openings

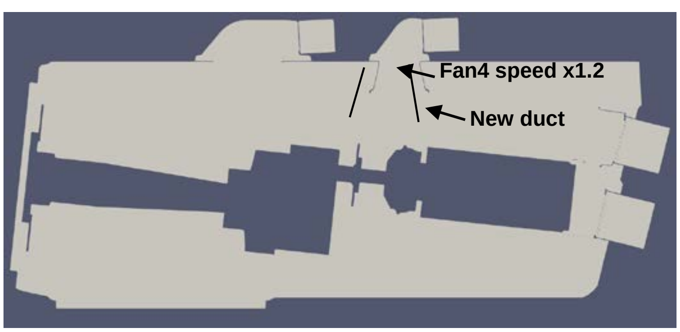

Fig. 6. Case III with new duct above coupling and fan4 speed increased by 20%

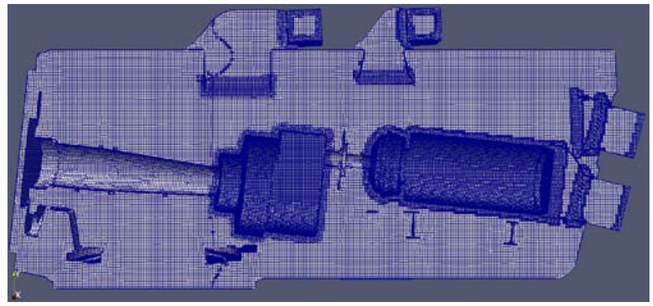

Fig. 7. Cut section of mesh at mid plane for case I

Three cases are built shown in figure 4,5 and 6. Pre-processing is done using Salome software. Case I is baseline case and comparative study of results for case II and III will be done against case I. Bottom openings are closed in case II simulation. Further in case III along with closed bottom openings an additional duct is provided above the coupling and fan4 speed is increased by 20%. The duct is provided to channelize the air flow above coupling region for better cooling around coupling region. Meshing is done using blockMesh and snappyHexMesh utility which is available with OpenFoam software package. Mesh element count is 4 million cells along with two boundary layers with total thickness of 6mm.

6. RESULTS & DISCUSSION

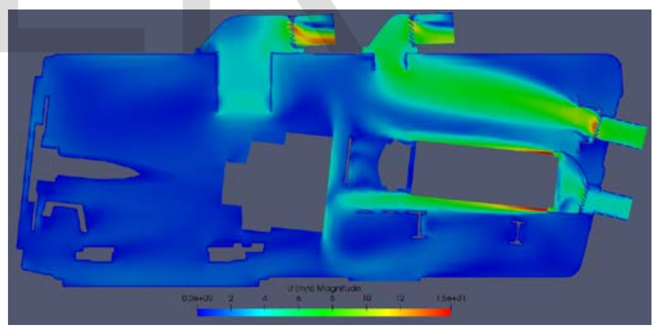

Fig. 8. Case I - Velocity Contour

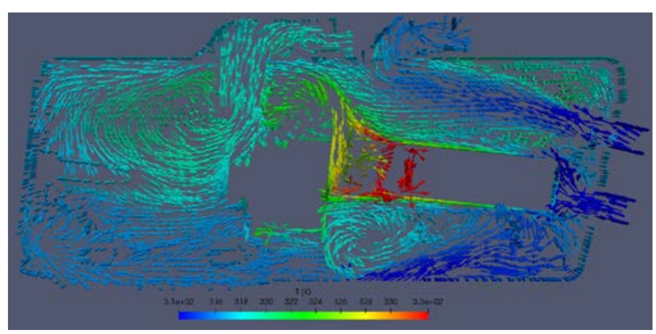

Fig. 9. Case I - Temperature Vectors

Solver used in OpenFoam is chtMultiRegionSimpleFoam. Contours and vectors are plotted at mid-section plane along the length of nacelle in ParaView software. Figure 8 and 9 show the velocity contour and temperature vectors for case I – baseline case. It can be observed that fan4 only carries away cold air coming in from fan1 thus does not contribute in effective cooling of coupling and nearby region. The temperature data obtained for heat source components after 6000 iterations is –

Table 3. Temperature Data for case I

Temperature Data		
Coupling (°C)	Generator (°C)	Gearbox (°C)
575	151	69

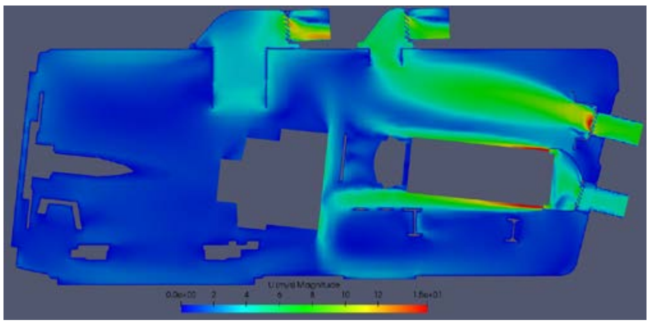

Fig. 10. Case II – Velocity Contour

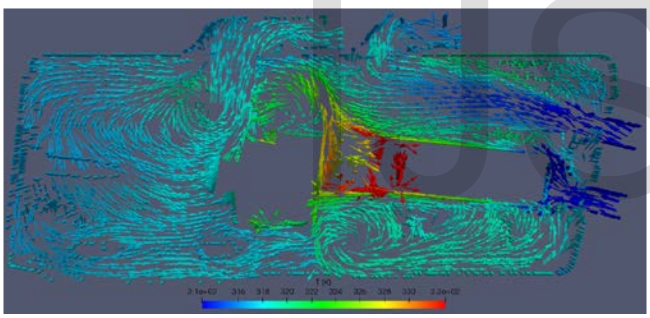

Fig. 11. Case II – Temperature Vectors

Figure 10 and 11 show the velocity contour and temperature vectors for case II – no bottom openings. It can be observed that the whole temperature distribution inside the nacelle changes. Temperature is equally distributed inside the nacelle. A drop of 6°C is observed for coupling and 3°C for generator in comparison with baseline case. The temperature data obtained for heat source components after 6000 iterations is –

Table 4. Temperature Data for case II

Temperature Data		
Coupling (°C)	Generator (°C)	Gearbox (°C)
569	148	68

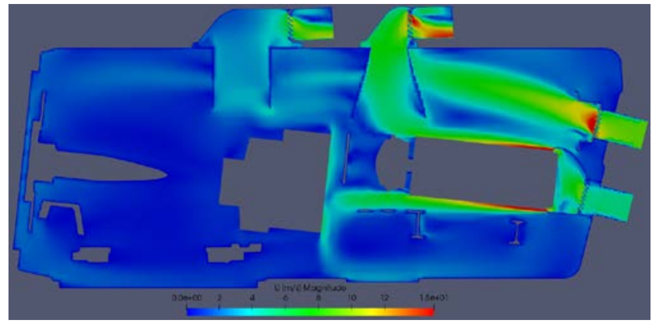

Fig. 12. Case III - Velocity Contour

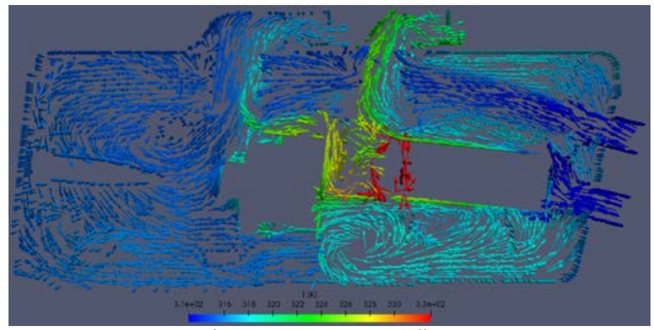

Fig. 13. Case III - Baseline Case

Figure 12 and 13 show the velocity contour and temperature vectors for case III – with new duct above coupling and fan speed increased by 20%. It can now be observed that fan4 carries away hot air from coupling region and thus effectively reduces the coupling and generator temperature. A drop of 13°C is observed for coupling and 7°C for generator in comparison with baseline case. The temperature data obtained for heat source components after 6000 iterations is –

Table 5. Temperature Data for case III

Temperature Data		
Coupling (°C)	Generator (°C)	Gearbox (°C)
562	144	68

After studying above three cases we can summarize the results in following points -

- The bottom openings in nacelle cover do not help in cooling of coupling as they provide restriction to fan2 flow.
- If the bottom openings are closed then the flow rate of fan2 increases. This provides more cooling effect in coupling and generator region as fan2 performance increases.
- For further cooling of coupling and generator a new extended fan4 duct design is designed along with fan4 speed increased by 20%.

6. CONCLUSION

Temperature drop of 13°C is observed for coupling and 7°C for generator if we increase fan4 speed by 20% along with new duct design above the coupling with no bottom openings in nacelle cover i.e. case III because mass flow rate increases due to increase in fan speed with extended duct and thus more cooling effect is achieved in coupling and generator region. If current power of fan4 is x KW. According to fan laws, if we increase the fan speed by 20% then power increases by 66%. Fan with power of almost 1.66x KW or higher is required to achieve improvement in cooling of coupling. The high unrealistic values of temperature are due to various assumptions made for geometry and input data during simulation. These values are only used for comparative study only. The best case selected i.e. case III for improvement in cooling of coupling can be validated after testing.

REFERENCES

[1]. Rakshantha Mohan, Senthilkumar Sundararaj, Kannan Budda Thiagarajan, "Numerical Simulation of Flow Over Buildings Using OpenFOAM", (2019), The 11th National Conference on Mathematical Techniques and Applications AIP Conf. Proc. 2112, 020149-1–020149-7.

[2]. Xu Chu, Guang Yang, Sandeep Pandey, Bernhard Weigand, "Direct Numerical Simulation of Convective Heat Transfer in Porous Media", (2019), International Journal of Heat and Mass Transfer, Volume 133, Pages 11-20.

[3]. Antonio Gomez, Carlos Montanes, Miguel Camara, Ana Cubero, Jose Manuel Munoz, "An OpenFOAM-based Model for Heat-exchanger Design in the Cloud," (2018), Applied Thermal Engineering, Volume 139, Pages 239-255.

[4]. Omid Nematollahi, Kyung Chung Kim, "Wind Turbine Cooling: the State-of-the-Art Review", (2017), Proceedings of Academics World International Conference, Tehran, Iran.

[5]. M. A. Mahdi, A. Smaili, "Numerical Investigations of the Thermal Behaviour of HAWT Nacelle using ANSYS FLUENT", (2017) Energy Procedia 141, Pages 394-398.

[6]. Abdelhakim Limane, Hachimi Fellouah, Nicolas Galanis, "Simulation of Airflow with Heat and Mass Transfer in an Indoor Swimming Pool by OpenFOAM", (2017), International Journal of Heat and Mass Transfer, Volume 109, Pages 862-878, June 2017.

[7]. M. A. Mahdi, A. Smaili, "On Clean Cooling System for Wind Turbine Nacelle Operating in Hot Climate", (2015), International Conference en Clean Cooling Technologiesin the MENA Regions, ICT3_MENA'201.

[8]. Arturo De Risi, Marco Milanese, Gianpiero Colangelo, Domenico Laforgia, "High Efficiency Nanofluid Cooling Systems for Wind Turbines", (2014), Università del Salento, Dipartimento di Ingegneria dell'Innovazione via per Arnesano, 73100, LECCE (LE), Italy.

[9]. M. F. Uth, Y. Jin, A. Kuznetsov, H. Herwig, "A Direct Numerical Simulation Study on the Possibility of Macroscopic Turbulence in Porous Media: Effects of Different Solid Matrix Geometries, Solid Boundaries, and Two Porosity Scales", (2016), Phys. Fluids 28 (6) 065101.

[10]. G. Yang, B. Weigand, A. Terzis, K. Weishaupt, R. Helmig, "Numerical Simulation of Turbulent Flow and Heat Transfer in a Three-Dimensional Channel Coupled with Flow Through Porous Structures", (2018), Transp. Porous Media 122 (1), Pages 145–167.

[11]. G. Yang, J. Wu, "Effect of Side Ratio and Aiding/Opposing Buoyancy on the Aerodynamic and Heat Transfer Characteristics Around a Rectangular Cylinder at Low Reynolds Numbers", (2013), Numer. Heat Transf., Part A: Appl. 64 (12), Pg. 1016–1037.

[12]. Klaus Hoffmann, Steve Chiang, Computational Fluid Dynamics Volume I, A Publication of Engineering Education System, Kansas, USA, (2000), Reference Book.

[13]. A. Limane, H. Fellouah, N. Galanis, "Thermo-Ventilation Study by Openfoam of the Airflow in a Cavity with Heated Floor", (2015) Build. Simul. 8, Pages 271–283.

[14]. D.Y. Shang, B.X. Wang, "The Deviation of Heat Transfer Calculation for Laminar Free Convection of Gas Due to Ignoring the Variable Thermophysical Properties", (1993) Wärme- und Stoffübertragung 28, 33–36.