HEFAT2014
10th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics
14 – 16 July 2014
Orlando, Florida

THERMAL ANALYSIS OF WIND TURBINE NACELLE OF 2.5 MW TURBINES AT WINTER CONDITIONS

Kadir Nuri Tekin, Tahir Yavuz
and Emre Koç
*Author for correspondence
Department of Mechanical Engineering,
Baskent University,
Ankara 06810,
TURKEY.,
E-mail: tyavuz@baskent.edu.tr

ABSTRACT

A numerical method for analysing and quantifying the thermal behaviour of wind turbine nacelle of 2.5 MW operating in the extreme winter conditions have been presented. The effects of the extreme external temperatures of -30°C, -20 °C and -10°C on the electrical equipment and mechanical components within the nacelle have been determined at the design wind speed of 12 m/s. Two cases, open and closed system applications, have been considered. For both cases without the AC at T_{ext}=-30°C,the surface temperatures of the gear box and generator are outside the temperature limits. When applying the AC to the systems, temperatures became inside the operation temperature limits. For closed system applications at T_{ext}=-30 °C and -20 °C, the surface temperatures of all components are inside the temperature limits with the capacities of the AC system, 5 kg/s at 0 °C, 5 kg/s at 10°C with some icing problems inside wall of the nacelle. For closed system applications at T_{ext}=-10°C, the surface temperatures of components are inside the temperature limits with the AC capacities of 4 kg/s at 30°C, 5 kg/s at 0°C, 5 kg/s at 5°C and 5 kg/s at 10°C without icing problems. The simulation results have confirmed that, to maintain an acceptable temperature levels inside the nacelle and on the components for typical winter conditions, the air conditioning systems are needed. The air conditioning systems of the nacelle have to be optimized and adjusted properly as functions of wind turbines rated power, external wind velocity and temperatures.

INTRODUCTION

Wind turbines in cold climates are exposed to icing conditions and low temperatures outside the design limits of standard wind turbines. Standard turbines operating in such extreme environments are prone to production losses and increased loads, which in turn will cause a risk of premature mechanical failure and financial losses. Cold Climate (CC) areas are regions where icing events or periods with temperatures below the operational limits of standard wind turbines occur, which may impact project implementation, economics and safety. There are three general issues important to the operation of wind turbines in cold climate[1]. Low Temperature Climate(LTC) is the area where periods with temperatures below the operational limits of standard wind turbines occur, Icing Climate(IC) is the areas where icing events and Snowing Climate(SC). Although theoretically possible, active icing rarely occurs at temperatures below-25°C. Wind turbines in cold climates refer to sites that have either icing events or low temperatures outside the operational limits of standard wind turbines. International Energy Agency, IEA R&D Wind has started a new annex, Wind Energy in Cold Climates. This is an international collaboration on gathering and providing information about wind turbine icing and low temperature operation. The goal is to monitor reliability of standard and adapted technology and establish guidelines for applying wind power in cold climates. Consequently, the wind farm developers are confronted with a lack of information when planning wind farms in a cold and hot weather environments[2]. International Energy Agency, IEA R&D Wind has started a new annex, Wind Energy in Cold Climates.

This is an international collaboration on gathering and providing information about wind turbine icing and low temperature operation. More details are given in References [6, 7, 8 and 9]. Also; more information about wind turbine in cold climate is given in Ref[1]. Limited effort has been made to assess the potential of wind development in CC and CC-like microclimates. Tammelin et al., [3], report potential markets of 20% of the installed capacity by 2010. This outdated estimate would correspond to wind power worth of some 40 GW in CC, if combined with the forecast for 2010 wind production presented in BTM's 2011 World Market Update. There is, however, an inherent lack of market studies for the potential of wind energy in CC. The main reason for this has been a natural choice to focus initially on sites where no CC adoption is required. There are few work on the thermal analysis of the wind turbines. Lacroix and Manwell[4] provides an overview of the issues affecting wind turbine operations in cold weather with a special emphasis given on atmospheric conditions prevailing in the Northeast United States. In addition, this paper suggests ideas of further research on the operation of wind turbines in cold climate. It also identifies organizations interested by similar issues whose cooperation would be beneficial. Parent and Ilinca[5] conducted critical review on anti-icing and de-icing techniques for wind turbines. Review includes precipitation, atmospheric and in-cloud icing affect wind turbine operation in various ways, including measurement and control errors, power losses, mechanical and electrical failures and safety hazard. Anti-icing and de-icing strategies are used to minimize these effects. Active heating of blades is the most tested, used and reliable way to prevent icing effects. Laako et al[6]. curried out a work on the effects of the weather conditions on the turbine operations. Wind turbines in cold climates refer to sites that may experience significant time or frequency of either icing events or low temperatures outside the op-erational limits of standard wind turbines. The goal of the cooperation is to monitor reliability of standard and adapted technology and establish guide-lines for applying wind power in cold climates . Smaili et al[7], curried out a detailed work on Thermal Behaviour of a Wind Turbine Nacelle Operating in a Nordic Climate conditions. This article focuses on the effects of external air temperature, wind velocity, and the heat rate released by an electrical generator on the spatial distribution of the temperature inside the nacelle.

In this study, we are concerned only, the thermal behaviour of the nacelle of the wind turbine rated power at 2.5 MW in winter conditions such as only the low temperature climate. The cases of icing and snowing were not considered in the paper. Detailed results, including the flow and temperature fields around and throughout the nacelle and on the components in the nacelle under typical wind velocity of 12 m/s and the minimum external air temperatures of -30^{o}C are presented for open and -30^{o}C, -20^{o}C , -10 ^{o}C and 0 ^{o}C for closed system nacelle applications.

MATHEMATICAL FORMULATIONS AND DEFINITIONS OF SYSTEM

The external air flow around the nacelle and rotor, as well as the internal air flow through the nacelle described by the Reynolds averaged Navier-Stokes equations. The energy equations are solved to account for the heat transfer effects, and to determine how to cool down or heat up in nacelle by using an air-conditioning system to keep the temperature in an acceptable operating level in the range of temperature,-30^{o}C to 0^{o}C. The details information about the mathematical formulations was given in [8].

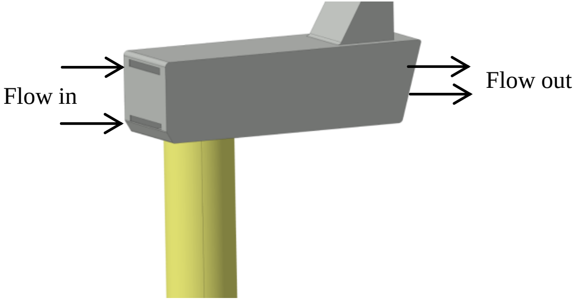


Figure 1 Geometries of the nacelle

The nacelle of the 2.5 MW turbines consisting of generator, gearbox and electronic equipment are defined as 11.5 m x 4 m x 3.5 m in dimensions. Referring Nordex[9] the geometry of the nacelle was chosen and two geometries, close and partial open systems, were considered Figure 1. The generator is chosen as brushless synchronous generator and gear box has 2-stage differential planetary and 1-stage helical gear .

For closed system applications, there is no flow circulation within the nacelle. In this case, the heat exchange between the electrical generators (generator, gear box and electrical box) with the surrounding. The exchanged between nacelle and its surrounding should be minimized. During the extreme winter conditions, the nacelle should be well insulated thermally and impermeable. Therefore, for the winter conditions, the closed system nacelle rather than the open system was considered. Only, front inlet open system of nacelle was considered for the comparison. Open system applications applicable for the summer conditions have to be studied in details in Ref [8].

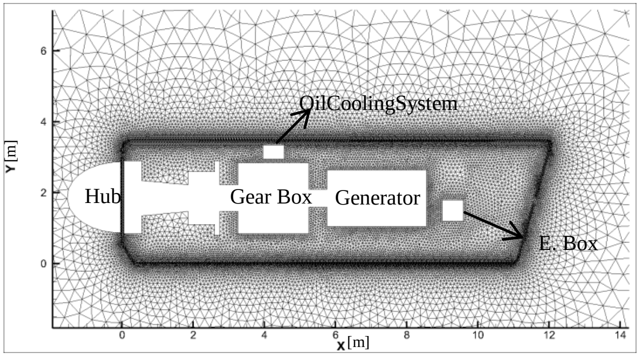


Figure 2 Geometry and unstructured grid of nacelle for CFD Analysis

The flow field in the vicinity of the turbine and nacelle immersed in a uniform incoming flow parallel to the turbine axis of rotation is axisymmetric. Thus, the computational domain consists of a cylinder that includes the rotor and nacelle. Fig. 2 shows a (x; y) section of the domain. Flow is considered to be a steady turbulent flow throughout nacelle for open system and no flow within the nacelle for closed system. The electrical generator and gear box being simulated as heat sources. Heat losses from generator with generator heat exchanger, gear box with gear box oil cooling system and electrical box containing control units and electronic circuits. The total heat released from system (considered to be 3%, 12% and 1% with respect to the rated power of the wind turbine of 2.5 MW for gear box, generator and electrical equipment respectively) is about 400 kW [10].

The computational domain consists of a cylinder that includes the rotor and nacelle. The FLUENT code was used as the advanced tool in this study. Referring the length of the nacelle, L, the grid extends from 2L upstream to 1.5L downstream. The upper and lower boundary extends 2L from the nacelle. This domain is discretized into unstructured meshes composed of triangular elements. The complete set of fluid equations, expressed in axis-symmetrical coordinate system, consists of the continuity equation, three momentum equations for transport of velocity, and the energy equation for heat transfer effects, as well as two equations for modelling turbulence kinetic energy and the turbulence energy dissipation. The solution of the resulting mathematical model is accomplished by employing the unstructured CVFEM formulation mentioned above.

Boundary conditions are (Table 1); the velocity field as well as the k-ε properties are set to uniform and a uniform temperature profile is prescribed, equal to undisturbed temperature T_{ext} at inlet. The velocity and temperature fields as well as the k-ε properties are calculated using the outflow treatment while pressure is specified and assumed to be uniform at outlet[7]. Turbulent properties and velocity fields are prescribed with the wall function methods in the wall regions of the nacelle.

Table 1. Boundary Conditions

Component	Descriptions	Properties
Inlet	Velocity Inlet	--------------------
Outlet	Out Flow	--------------------
Generator	Wall	Heat Generation
Gear box	Wall	Heat Generation
Electrical Box	Wall	Heat Generation
Generator Heat Exch.	Heat Exchanger	--------------------
Gear box Oil Cooler	Heat Exchanger	--------------------
Nacelle Outer Surface	Wall	--------------------

Numerical Models

The FLUENT code was used as the advanced tool in this study. Detailed analysis was made using the FLUENT code including Spalart-Allmaras', k-ε turbulent model. The results are all obtained for two dimensional computations although three dimensional effects are present within the separated region. No-slip boundary conditions are used at solid surfaces. The grid used for the nacelle is generated by the GAMBIT program. Different size grids are used to ensure grid independence of the calculated results. This is achieved by obtaining solutions with increasing number of grid nodes until a stage is reached where the solution exhibits negligible change with further increase in the number of nodes. The FLUENT code solves the RANS equations using finite volume discretization. Second-order upwind discretization in space is used, and the resulting system of equations is then solved using the SIMPLE coupled solution procedure until certain convergence criteria are satisfied. The convergence rate is monitored during the iteration process by means of the residuals of the dependent variables of the governing differential equations. The results of the numerical calculation obtained have been tested by the results obtained by Smaili et al[7]. Model outlined above was adapted to the Smaili model of 600 kW turbines. In this model the external temperature and wind velocity are chosen as 25^oC and 7 m/s respectively. Results of surface temperature distributions of generator determined by these two models have been compared. The maximum surface temperature obtained by Smaili is about 40^oC compared with the temperature of 42^oC determined from the present study. As seen there are about 2^oC or 3^oC temperature differences between two results. These differences can be attributed to the geometric differences and some uncertainties of these two models. Therefore the mathematical model being used in the present study can be acceptable.

RESULTS AND DISCUSSIONS

Wind turbines should be designed to operate under severe weather conditions. Particular attention should be paid to the electrical equipment and mechanical components located within the nacelle, as they may be subjected to extremely high temperature gradients, resulting in contradictory design requirements. Therefore, to assess the effect of the external environment on the electrical equipment and mechanical components, the air flow and temperature fields within and around the nacelle were computed for the extreme temperatures of -30^oC at the design wind speed of 12 m/s. The total heat released from system for the rated power of the wind turbine of 2.5 MW is about 450 kW[10]. Temperature limits of the electrical box, and gear box - generator are 80^oC and 150^oC respectively and the optimum operating temperature range of the generator is from 80^oC and 125^oC [9].

When the closed system configuration was adopted, there is no flow circulation within the nacelle. In this case, heats exchange between the electrical generator, gear box and other components inside the nacelle. Figure 3 shows the simulation results of the temperature and velocity fields obtained at the external temperatures of -30^oC for closed system application whereas Figure 4 represents results for open system applications without air conditioning. As seen then temperature within the nacelle varies from 302K to 380K in winter condition for closed system application, while temperature inside the nacelle varies from 250K to 325K for the open system application. Minimum temperatures are obtained on the surfaces of the gear box. Velocity field shows that the velocity reaches to the maximum value of 15 m/s at the front corners of the nacelle and the range of the velocity in the nacelle is about 1 m/s obtained in the open system application. As results, there is a need an air-conditioning system to keep temperature within the nacelle in the operational limits of the components.

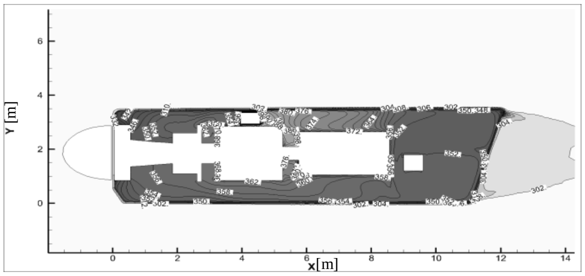


Figure 3.a. Temperature[K] distribution around nacelle for the open system application, T_{ext}=-30°C

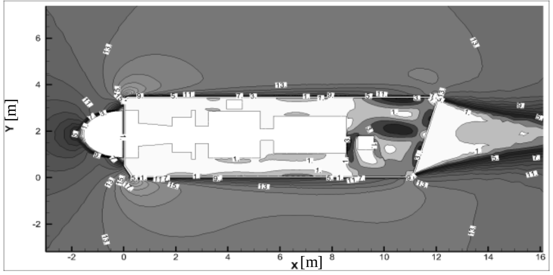


Figure 3.b. Velocity distribution around nacelle for the open system application, T_{ext}=-30°C

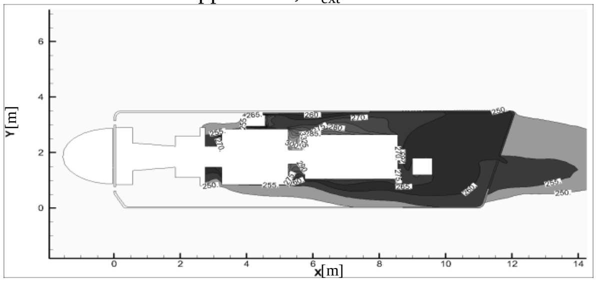


Figure 4.a. Temperature[K] distribution around nacelle for the open system application, T_{ext}=-30°C

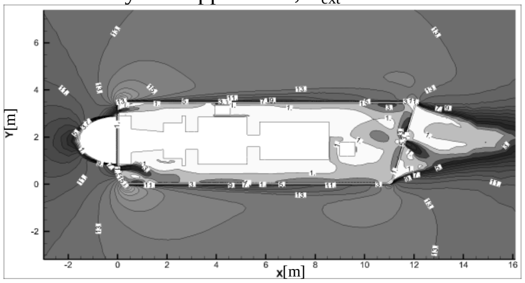


Figure 4.b. Velocity distribution around nacelle for the open system application, T_{ext}=-30°C

The 2D simulations have been conducted on the four different external temperatures of -30^{o}C, -20^{o}C, -10 ^{o}C and 0^{o}C for various cases of air-conditioning systems at the external wind speed of 12 m/s. Variations of the surface temperatures of components in the nacelle at Text= -30^{o}C obtained are presented in Figure 5. As seen, for both cases of open and closed systems without the AC system, surface temperature of the gear box is outside of the operation temperature limit. When applying the AC to the system, 5 kg/s at 0^{o}C, it became inside the operation temperature limit with some icing problems on the wall of the nacelle. The effects of various capacities of the AC systems on the temperatures are shown in the figure.

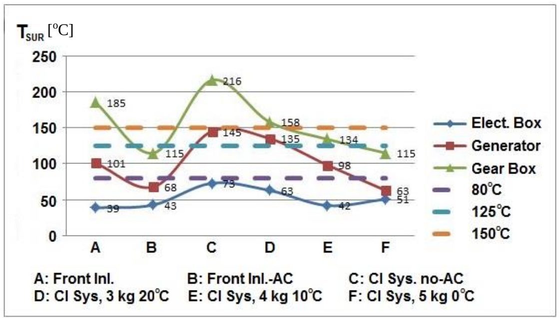


Figure 5 Variation of the surface temperatures of components in surface the nacelle with the cases, T_{ext}=-30^{o}C, V_{ext}=12 m/s

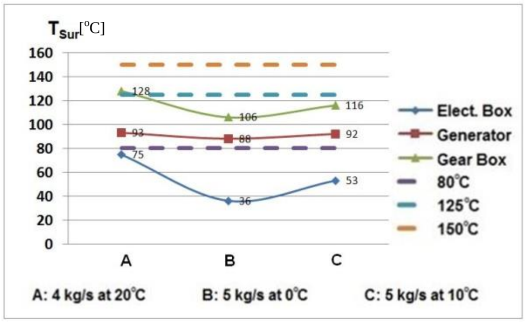


Figure 6 Variation The effect of the AC capacities on the temperatures of the components, T_{ext}=-20^{o}C, V_{ext}=12 m/s

The effect of the AC Capacity on the surface temperatures of the components for closed system application at Text=-20^{o}C are shown in Figure 6. As seen, for the case of closed system with the AC of 5 kg/s at 0^{o}C and 5 kg/s at 10^{o}C, surface temperatures of the all components are in the operational temperature limits. But all these conditions, the minimum temperature on the inside wall of the nacelle is about -14^{o}C and -10^{o}C respectively (Figure 9). Consequently, there is some freezing situation on the surface of the nacelle. For the case of the AC with 4 kg/s at 20 ^{o}C, the surface temperature of the wall of the nacelle is about 3^{o}C and there is no freezing situation happened in the nacelle.

Results obtained at Text= -10^{o}C, are presented in Figure 7.For all cases, the surface temperatures of components are inside the range of the operation temperatures. But, for the case of the AC, 5 kg/s at 0^{o}C, there is some icing problem inside the nacelle.

Results obtained at Text=0^{o}C are presented in Figure 8. As seen, the surface temperatures of the components depend on the AC capacity. All cases the surface temperatures of components are inside the temperature limits. Also, all cases, the surface temperatures of the inside wall of the nacelle have positive values and consequently, there is no icing problems.

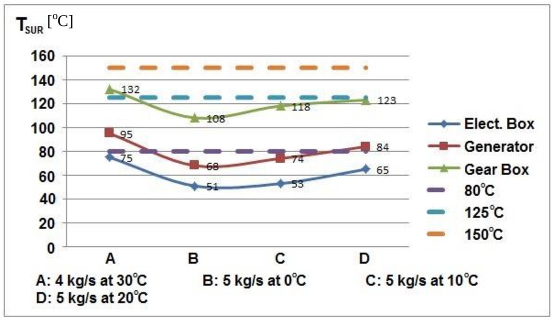


Figure 7 The effect of the AC capacity on the surface of the components, T_{ext}=-10^{o}C, V_{ext}=12 m/s

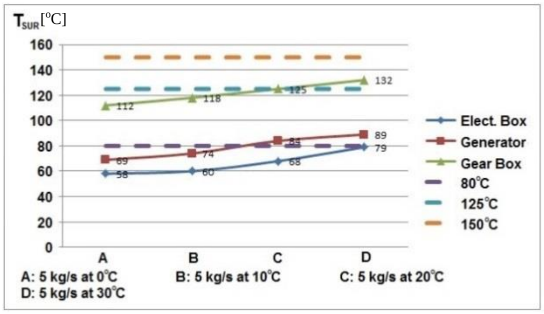


Figure 8 The effect of the AC capacity on the surface of the components, Text=0^{o}C, Vext=12 m/s

Three dimensional simulations have also applied to the system. The contours of the surface temperatures of components and inside the nacelle have been presented for various cases. The results obtained for various cases are outlined in Figure 9.

Front Inlet Without the AC (Figure 9a): The surface temperatures of components; Generator between 30^{o}C and 101^{o}C, Gear box between 10^{o}C and 185^{o}C, electric box between -8^{o}C and 39^{o}C. Also, these values are comparable with the values obtained from the 2D analysis in Figure 5. Temperatures of the gear box oil cooler vary from -25^{o}C to -11^{o}C while the temperature of the generator heat exchanger changes from -30^{o}C to -20^{o}C. Thus, the range of the temperature variations in the nacelle varies from -30^{o}C to 185^{o}C. Thus there is an icing problem inside the nacelle.

Front Inlet with the AC, 5 kg/s, 0^{o}C (Figure 9b): The variations of the surface temperatures of components; Generator from 28^{o}C to 68^{o}C, Gear box from 10^{o}C to 115^{o}C, electric box from 7^{o}C to 43^{o}C. Temperatures of the gear box oil cooler varies from -14^{o}C to 23^{o}C while the temperature of the generator heat exchanger changes from -30^{o}C to -14^{o}C.The range of the temperature variations in the nacelle walls varies from -25^{o}C to -15^{o}C. Consequently, there is icing problems inside the nacelle.

Closed system without the AC(Figure 9c): Temperature variations are; Generator between 78^{o}C and 145^{o}C, Gear box between 89^{o}C and 216^{o}C and electric box between 68^{o}C and 79^{o}C. Temperatures of the gear box oil cooler vary from -54^{o}C to 82^{o}C while the temperature of the generator heat exchanger changes from -30^{o}C to 2^{o}C. The minimum temperature obtained on the nacelle walls is about -30^{o}C and consequently, there is an icing problem.

Closed system with AC, 5kg/s at 0^{o}C, Text=-30^{o}C(Figure 9d): Temperature variations; Generator between 32^{o}C and 57^{o}C, Gear box between 32^{o}C and 77^{o}C, and electric box between 25^{o}C and 43^{o}C. The range of the temperature variations in the nacelle varies from -18^{o}C to 57^{o}C, and there is some icing problem. Front inlet without AC,T_{ext}=-30^{o}C(**Figure 9e**).The range of the temperature variations in the nacelle are from -3^{o}C to 53^{o}C. Temperature variations in the nacelle for other two cases are presented in Figure 9f and Figure 9g. Thus, the air-conditioning systems are required to keep the system temperatures in operational temperature ranges.

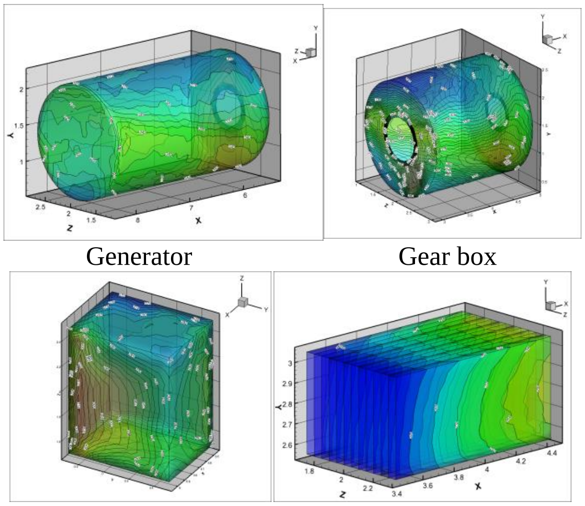

Generator Gear box
Elect. box Gen. Heat Exchanger

Figure 9a. Temperature distributions on the components in the nacelle, front inlet without the AC, T_{ext}= -30^{o}C.

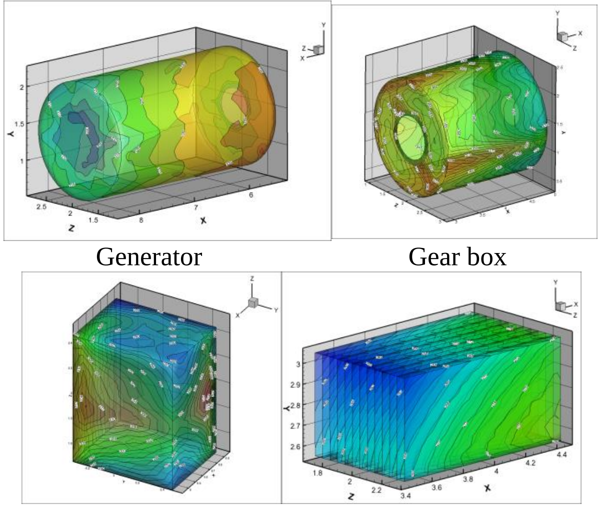
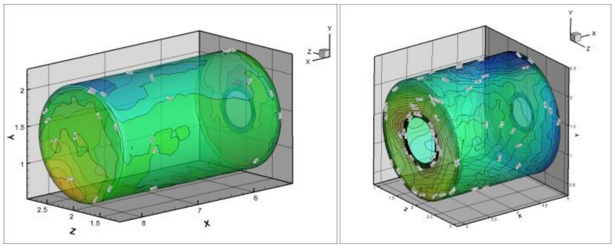
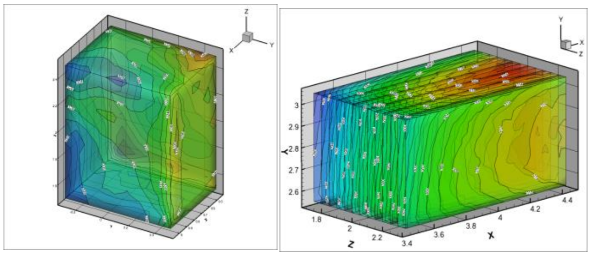

Generator Gear box
Elect. box Gen. Heat Exchanger

Figure 9b. Temperature[K] distributions on the components in the nacelle, Front inlet with AC, 5 kg/s at 0^{o}C,Text=- 30 ^{o}C.

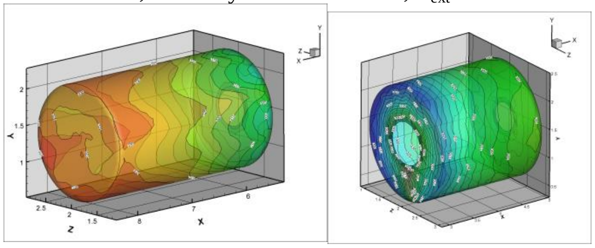


Generator Gear box

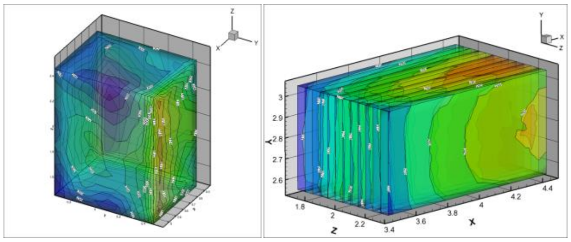


Elect. box Gen. Heat Exchanger

Figure 9c. Temperature[K] distributions on the components in the nacelle, closed system without AC, T_{ext}=-30 °C



Generator Gear box



Elect. box Gen. Heat Exchanger

Figure 9d. Temperature[K] distributions on the components in the nacelle, closed system with AC, 5 kg/s at 0°C,T_{ext}=-30 °C.

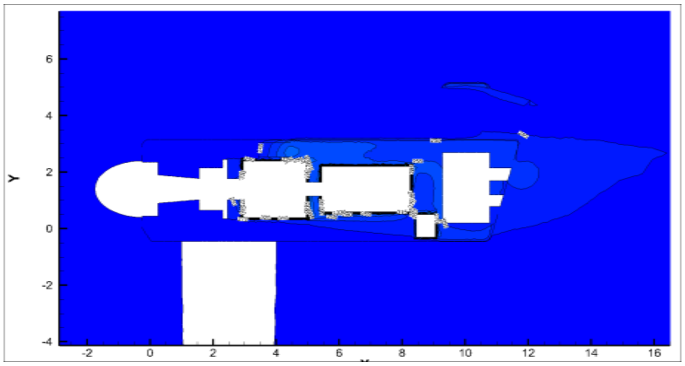


Figure 9e. Temperature variation inside the nacelle, Front inlet without AC, T_{ext}=-30°C

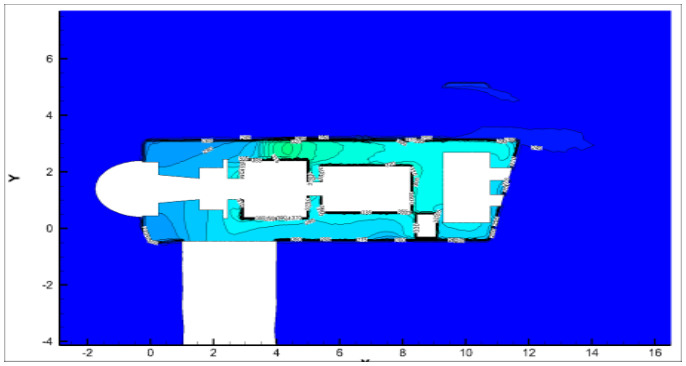


Figure 9f. Temperature[K] variation inside the nacelle, Closed, without AC,T_{ext}=-30°C

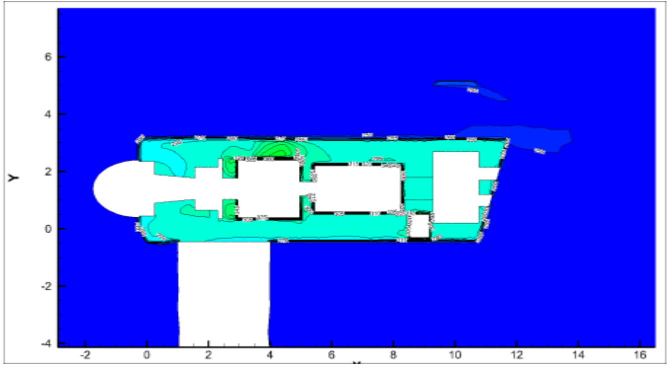


Figure 9g. Temperature[K] variation inside the nacelle, Closed system with AC,4kg/s at 20°C

CONCLUSIONS

A numerical method for analysing and quantifying the thermal behaviour of wind turbine nacelle of 2.5 MW, operating in the extreme winter conditions has been presented. The effects of the external environment on the electrical equipment and mechanical components, the air flow and temperature fields within and around the nacelle were computed for the extreme temperatures of -30°C,-20°C, -10 °C and 0 °C at the design wind speed of 12 m/s.

For open and closed system application systems without the AC at T_{ext}=-30°C,the surface temperature of the gear box and generator are outside of the temperature limits. When applying the AC to the system, 5 kg/s at 0°C, it became inside the operation temperature limit. Depending on the capacity of the AC system, there are some icing problems in the nacelle.

For closed system applications;

At T_{ext}=-20 °C, the surface temperatures of all components are inside the temperature limits with the capacities of the AC systems, 5 kg/s at 0 °C, and 5 kg/s at 10°C. But all these conditions, the minimum temperature on the inside wall of the nacelle is about -14 °C and -10 °C respectively and, consequently there are some icing problems. For the case of the AC, 4 kg/s at 20°C, all surface temperatures are inside the temperature limits and the minimum temperature obtained on the wall of the nacelle is about 3 °C, and no icing problems.

At T_{ext}=-10°C, the surface temperatures of components are inside the temperature limits with the AC capacities of 4 kg/s at 30°C, 5 kg/s at 0°C, 5 kg/s at 5°C and 5 kg/s at 10°C. But, for the case of the AC, 5 kg/s at 0°C, there is some icing problem inside the nacelle.

At Text=0^{o}C,the surface temperatures of the components depend on the AC capacity. All cases the surface temperatures of components are inside the temperature limits. Also, all cases, the surface temperatures of the inside wall of the nacelle have positive values and consequently, there is no icing problems.

Thus, the wind turbine operating in the winter condition needs the AC system to keep temperatures of the components inside the operation limits. The capacity of the AC systems has to be determined as functions of the external temperature and wing turbine rated power.For the extreme winter conditions, the nacelle of wind turbine has to be isolated from outside to avoid the icing problems inside the nacelle.

REFERENCES

[1] Baring-Gould I., et. all., "Wind Energy Projects in Cold Climates", Expert Group Study on Recommented Pratices, May22 2011, IEA Wind.

[2] Wind Energy Projects Throughout the United States. Data from the web site: American Wind Energy Association, AWEA (2000) - http://www.awea.org/projects/index.html.

[3] Tammelin, B., M. Cavaliere, H. Holttinen, C. Morgan, H. Seifert, and K. Säntti, "Wind Energy Production in Cold Climate", Meteorological Publications No. 41, Finnish Meteorological Institute, Helsinki. 41 pp. ,2000.

[4] Lacroix, A and Manwell,J.F. "Wind Energy: Cold Wheader Isues", University of Massachasetts at Amhers, Renewable Research Laboratory, June 2000.

[5] Parent, O and Ilinca, A. "Anti-icing and de-icing techniques for wind turbines: Critical Review", Cold Region Science and Technology 65, 88-96,2011.

[6] Laakso T.,Holttinen H., Ronsten G., Tallhaugn L, Horbaty R., Baring-Gould I., Lacroix A., Peltola E. And Tammelin B. "State-of-the-art of wind energy in cold climates" , IEA, April 2003

[7] Smaïli, A. , Masson, C. , Taleb, S. R. and Lamarche, L.(2006) "Numerical Study of Thermal Behavior of a Wind Turbine Nacelle Operating in a Nordic Climate", Numerical Heat Transfer, Part B: Fundamentals, 50: 2, 121-141.

[8] Tekin, K. N., T. Yavuz and E. Koç, "Thermal Analysis of Wind Turbines Nacelle of 2.5 MW at Summer Conditions", send to the publications in Applied Energy, 2014.

[9] Nordex Energy GmbH, Germany, 2013.

[10]Johnson, G. L., "Wind Energy Systems", Electronic Edition, 2001.