

**CFD MODELLING OF HORIZONTAL-AXIS WIND TURBINE AND
SOLAR CHIMNEY PERFORMANCES FOR POWER
GENERATION**

By

Amr Ahmed Abd-Elhamid Mohamed

A THESIS SUBMITTED TO THE
FACULTY OF ENGINEERING AT CAIRO UNIVERSITY
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE
IN
MECHANICAL POWER ENGINEERING

FACULTY OF ENGINEERING, CAIRO UNIVERSITY

GIZA, EGYPT

2014

**CFD MODELLING OF HORIZONTAL-AXIS WIND TURBINE AND
SOLAR CHIMNEY PERFORMANCES FOR POWER
GENERATION**

By

Amr Ahmed Abd-Elhamid Mohamed

A THESIS SUBMITTED TO THE
FACULTY OF ENGINEERING AT CAIRO UNIVERSITY
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE
IN
MECHANICAL POWER ENGINEERING

SUPERVISED BY

Prof. Dr. Essam E. Khalil

PROFESSOR, MECHANICAL POWER
DEPARTMENT

FACULTY OF ENGINEERING-CAIRO
UNIVERSITY

Dr. Amr Yehia Abdo

Dr. Omar A. Huzayyin

MECHANICAL POWER DEPARTMENT

MECHANICAL POWER DEPARTMENT

FACULTY OF ENGINEERING-CAIRO
UNIVERSITY

FACULTY OF ENGINEERING-CAIRO
UNIVERSITY

FACULTY OF ENGINEERING, CAIRO UNIVERSITY

GIZA, EGYPT

2014

**CFD MODELLING OF HORIZONTAL-AXIS WIND TURBINE AND
SOLAR CHIMNEY PERFORMANCES FOR POWER
GENERATION**

By

Amr Ahmed Abd-Elhamid Mohamed

A THESIS SUBMITTED TO THE
FACULTY OF ENGINEERING AT CAIRO UNIVERSITY
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE
IN
MECHANICAL POWER ENGINEERING

Approved by the Examine committee:

.....

Internal examiner and advisor: **Prof. Dr. Essam E. Khalil**

.....

Internal examiner: **Prof. Dr. Abdel-Wahed Fouad El-Dib**

.....

External examiner: **Prof. Dr. Osama Ezzat Abd El-Latif (Benha University)**

.....

FACULTY OF ENGINEERING, CAIRO UNIVERSITY

GIZA, EGYPT

2014

Engineer: Amr Ahmed Abd ELhamid Mohamed
Date of Birth: 1 / 10/ 1982
Nationality: Egyptian
E-mail: Amr_ptb@yahoo.com
Phone: +2 0100 0856566
Address: Downtown, Cairo, Egypt
Registration Date: 1 / 10 / 2012
Awarding Date: / /
Degree: Master of Science
Department: Mechanical Power Engineering



Supervisors:

Prof. Dr. Essam E. Khalil
Dr. Amr Yehia Abdo
Dr. Omar Huzayyin

Examiners:

.....
Prof. Dr. Essam E. Khalil
Prof. Dr. Abdel-Wahed Fouad El-Dib
Prof. Dr. Osama Ezzat Abd El-Latif - (Benha University)

Title of Thesis:

**CFD MODELLING OF HORIZONTAL-AXIS WIND TURBINE
AND SOLAR CHIMNEY PERFORMANCES FOR POWER
GENERATION**

Key Words: CFD, FLUENT, CFX, Aerodynamics, blade design, blade element momentum (BEM), horizontal wind turbine (HWT), solar energy, collector, chimney, solar chimney.

Summary: The thesis objective was to discuss and simulate an alternative solution for power generation, two sustainable energy sources have been selected to be simulated and investigated, therefore this thesis will be discussing utilizing of different kind of renewable energy system, they are the wind power energy which the simulation of Horizontal axis wind turbine (HAWT) has been done, and the solar energy which the solar chimney system has been modeled as well. Both system are very valuable and suitable to Egypt weather where the sources of wind and solar are available over the year.

ACKNOWLEDGEMENT

I wish to express my deepest gratitude to all of my supervisors Prof. Dr. Essam E. Khalil, Dr. Amr Yehia Abdo and Dr. Omar Huzayyin for their guidance, advice, criticism, encouragements and insight throughout the research.

I am very grateful to all of my family for their ultimate moral support and concern, and all my friends and colleagues who helped me for working in this master degree.

Table of Contents

TABLE OF CONTENTS	3
ABSTRACT	11
CHAPTER 1	13
INTRODUCTION.....	13
1.1. Introduction	13
1.1. Modern Wind Turbine Design.....	14
1.2. Components	15
1.2.1. Rotor	15
1.2.2. Drive train	16
1.2.2.1. Generator.....	16
1.2.3. Nacelle	16
1.2.4. Tower and foundation	16
1.2.5. Electrical and control system	17
1.4. Solar chimney	17
1.4.1. Collector.....	18
1.4.2. Chimney.....	19
1.4.3. Energy storage in the collector.....	20
1.4.4. Turbine.....	21
1.5 Thesis Outline	22
CHAPTER 2	23
LITERATURE REVIEW.....	23
2.1. CFD Simulation	23
2.2. Main field of research:	23
CHAPTER 3	32
MATHEMATICAL MODEL	32
3.1 Introduction	32
3.1.1. Continuity equation	32
3.1.2. Momentum equations	32
3.2. General	33
3.2.1 Basic governing equations	33
3.3. Turbulence model	35
3.3.2. K- ω model of turbulence.....	35
3.3.3. K-e model of turbulence.....	36
3.3.3.1. Principle	36

3.3. Numerical aspects.....	38
CHAPTER 4	39
METHODOLOGY AND VALIDATION	39
4.1. Geometry of the Turbine.....	39
4.2. Airfoils and blade geometry.....	39
4.3. Pre-processing of wind turbine	44
4.4. Meshing of wind turbine:	46
4.4.1. Mesh Quality:.....	46
4.5. Boundary conditions.....	47
4.6. Solar chimney:	50
4.7. Pre-processing of solar chimney	50
4.8. Meshing of solar chimney:.....	52
4.8.1. Mesh quality:.....	54
4.9. Boundary conditions.....	55
4.10. Parametric study:	56
CHAPTER 5	57
RESULTS AND DISCUSSIONS	57
5.1. Results and discussion	57
5.2. Wake region study.....	58
5.2.1 Near and Far Wake.....	60
5.3. Rotor Aerodynamics	65
5.4. Stream lines of the air flow around the Blade:	68
5.4.1. Stream lines for the wind speed of 6.8 m/s:	68
5.4.2. Stream lines for the wind speed of 8 m/s.....	70
5.4.3. Stream lines for the wind speed of 10 m/s.....	73
5.5. Performance: CFD vs BEM.....	76
5.6. Results and discussion	77
5.6.1 Temperature counter	77
5.6.2. X-Y plot for the temperature vs. Flow path.....	78
5.6.3. Velocity vector counter	78
5.6.4. X-Y plot for the velocity profile along the chimney	79
5.7. Effect of the insolation on the flow stream through the solar chimney:.....	79
5.7.1. X-Y plot for the temperature vs. Flow path For Insolation values of 600 W/m ² , 800 W/ m ² , and 1000 W/ m ²	80
5.7.2. X-Y plot for the Velocity vs. Flow path For Insolation value of 600 W/ m ² , 800 W/ m ² , 1000 W/ m ²	81
5.7.3. X-Y plot for the density vs. Flow path For Insolation value of 600 W/ m ² , 800 W/ m ² , 1000 W/m ²	81
5.8. Effect of the Chimney height on the flow stream through the solar chimney:	82
5.8.1. X-Y plot for the temperature vs. Flow path for different chimney heights of 200m, 100 m, 50 m.	83
5.8.2. X-Y plot for the Velocity vs. Flow path for different chimney heights of 200m, 100 m, 50 m.....	84

5.8.3. X-Y plot for the density vs. Flow path for different chimney heights of 200m, 100 m, 50 m.	85
5.9. Effect of the Chimney Radius on the flow stream along the solar chimney:	86
5.9.1. X-Y plot for the temperature vs. Flow path for different chimney radius of 2m, 3 m, 4 m.	86
5.9.2. X-Y plot for the Velocity vs. Flow path for different chimney radius of 2 m, 3 m, 4 m.	87
5.9.3. X-Y plot for the density vs. Flow path for different chimney radius of 2 m, 3 m, 4 m.	88
5.10. Effect of the collector radius on the flow stream through the solar chimney:	89
5.10.1 X-Y plot for the temperature vs. Flow path for different collector radius of 50 m, 100 m, 150 m.	90
5.10.2. X-Y plot for the Velocity vs. Flow path for different collector radius of 50 m, 100 m, 150 m.	90
5.10.3. X-Y plot for the density vs. Flow path for different collector radius of 50 m, 100 m, 150 m.	91
5.11. Effect of the Roof height on the flow stream along the solar chimney:.....	92
5.11.1. X-Y plot for the temperature vs. Flow path for different roof heights of 1m, 2 m, 3 m.	93
5.11.2. X-Y plot for the Velocity vs. Flow path for different roof heights of 1m, 2 m, 3 m.	93
5.11.3. X-Y plot for the density vs. Flow path for different roof heights of 1m, 2 m, 3 m.	94
CHAPTER 6	96
CONCLUSIONS	96
REFERENCES.....	98
APPENDIX A	101
A. Wind turbine aerodynamics:.....	101
A.1. Actuator disc concept	101
A.2. Rotor disc theory	105

LIST OF FIGURES

Figure 1.1: Horizontal Axis Wind Turbine.....	14
Figure 1.2: The Major Components of A HAWT	15
Figure 1.3: Schematic layout of solar chimney power plant [11].....	18
Figure 1.4: Collector thermal balance scheme.....	19
Figure 1.5: principle of heat storage.....	20
Figure 1.6: solar chimney heat transfer mechanism.....	22
Figure 2.1: Blade surface meshing & rectangular containing the blade [12]	23
Figure 2.2: Cp curve vs. TSR (tip speed ratio) [12].....	24
Figure 2.3: Different relative velocity contours for stream lines of different sections of turbine blade [13].....	24
Figure 2.4: velocity contour prediction on the selected island due to interaction of the wind turbine with air [14].....	26
Figure 2.5: Turbulence intensity by U component [15].....	26
Figure 2.6: Turbulence intensity by Y component [15].....	27
Figure 2.7: Typical solar chimney scheme [16].....	27
Figure 2.8: Expected Solar radiation intensity for different locations in Egypt [17].....	29
Figure 2.9: Axis symmetry model- computational domain [18].....	30
Figure 2.10: Meshing increase at the corner of the solar chimney model [19].....	30
Figure 2.11: Numerical predication of roof exit as a function of insolation [20].....	31
Figure 2.12: Numerical predication of temperature for constant insolation [20].....	31
Figure 4.1: Airfoil configuration plotted in Q-blade... ..	41
Figure 4.2: Design of the blade in Q-blade	42
Figure 4.3.: Curves in Solid Works Front View.....	43
Figure 4.4: air foils distribution in solid works.....	43
Figure 4.5: Loft of curves in Solid Works.....	44
Figure 4.6: Final Blade.....	44
Figure 4.7: ANSYS Workbench project outline.....	45
Figure 4.8.: ANSYS Design Modeler.....	46
Figure 4.9: blade meshing.....	48
Figure 4.11: Boundary conditions implemented in ANSYS Meshing as named selections.....	49
Figure 4.12: Use of Periodic Boundaries.....	50
Figure 4.13.: ANSYS Workbench project outline for solar chimney.....	51
Figure 4.14.: Solar chimney complete model.....	51
Figure 4.15.: 5 degree solar chimney model (axis symmetry).....	52
Figure 4.16.: Solar power plant meshing.....	53
Figure 4.17.: Fine meshing for the solar chimney corner.....	53

Figure 4.18.: Meshing quality	54
Figure 4.19.: Name selection at meshing program.....	55
Figure 5.1: pressure distribution on the blade suction side.....	57
Figure 5.2: pressure distribution on the blade pressure side.....	57
Figure 5.3: The stream tube according to actuator disc theory [25].....	58
Figure 5.4: Flow stream expansion downstream the turbine.....	58
Figure 5.5: Flow stream expansion downstream the turbine	59
Figure 5.6: Flow stream expansion downstream the turbine	59
Figure 5.7. Iso-surface of computed vortices, $V = 6.8$ m/s [29]	60
Figure 5.8 Theoretical scheme of vortex structure [29]	61
Figure 5.9; velocity gradients at the wake region.....	61
Figure 5.10: Axial velocity contours $Y/D = -0.25$	62
Figure 5.11: Axial velocity contours $Y/D = -0.1$	62
Figure 5.12: Axial velocity contours $Y/D = 0$	63
Figure 5.13: Axial velocity contours $Y/D = 0.1$	63
Figure 5.14: Axial velocity contours $Y/D = 0.25$	64
Figure 5.15: Axial velocity contours $Y/D = 0.5$	64
Figure 5.16: Axial velocity contours $Y/D = 2.5$	65
Figure 5.17. : Velocity vectors at 25% span of the blade.....	66
Figure 5.18. : Velocity vectors at 50% span of the blade.....	66
Figure 5.19. : Velocity vectors at 75% span of the blade.....	67
Figure 5.20. : Velocity vectors at 95% span of the blade.....	67
Figure 5.21: Air Stream lines at 25% of the blade span with wind speed $V = 6.8$ m/s.....	68
Figure 5.22: Air Stream lines at 50 % of the blade span with wind speed $V = 6.8$ m/s.....	69
Figure 5.23: Air Stream lines at 75 % of the blade span with wind speed $V = 6.8$ m/s.....	69
Figure 5.24: Air Stream lines at 100 % of the blade span with wind speed $V = 6.8$ m/s.....	70
Figure 5.25: Air Stream lines at 25 % of the blade span with wind speed $V = 8$ m/s.....	71
Figure 5.26: Air Stream lines at 50 % of the blade span with wind speed $V = 8$ m/s.....	71
Figure 5.27: Air Stream lines at 75 % of the blade span with wind speed $V = 8$ m/s.....	72
Figure 5.28: Air Stream lines at 100 % of the blade span with wind speed $V = 8$ m/s.....	72
Figure 5.29: Air Stream lines at 25 % of the blade span with wind speed $V = 10$ m/s.....	73
Figure 5.30: Air Stream lines at 50 % of the blade span with wind speed $V = 10$ m/s.....	74
Figure 5.31: Air Stream lines at 75 % of the blade span with wind speed $V = 10$ m/s.....	75
Figure 5.32: Air Stream lines at 100 % of the blade span with wind speed $V = 10$ m/s.....	75
Figure 5.33. : Power output vs. Wind speed.....	76
Figure 5.34: Temperature contour through the solar chimney.....	77
Figure 5.35: Numerical prediction of the temperature profile through the chimney with insolation 800 W/m ²	78
Figure 5.36: Numerical prediction of the velocity vector profile through the chimney with insolation 800	

W/m ²	78
Figure 5.37: Numerical prediction of the velocity profile through the chimney with insolation 800- W/m ²	79
Figure 5.38. : Numerical prediction of the temperature profile through the chimney with different values of insolation	80
Figure 5.39. : Numerical prediction of the velocity profile through the chimney with different values of insolation	
Figure 5.40: Numerical prediction of the density profile through the chimney with variety of insolation value.....	82
Figure 5.41: Numerical prediction of the temperature profile through the chimney with different values of chimney heights.....	83
Figure 5.42.: Numerical prediction of the velocity profile through the chimney with different values of chimney heights.....	84
Figure 5.43.: Numerical prediction of the density profile through the chimney with different values of chimney heights.....	85
Figure 5.44: Numerical prediction of the temperature profile through the chimney with different values of chimney radius.....	86
Figure 5.45: Numerical prediction of the velocity profile through the chimney with different values of chimney radius.....	87
Figure 5.46.: Numerical prediction of the density profile through the chimney with different values of chimney radius.....	88
Figure 5.47: Numerical prediction of the temperature profile through the chimney with different collector radius values.....	89
Figure 5.48: Numerical prediction of the velocity profile through the chimney with different collector radius values.....	90
Figure 5.49: Numerical prediction of the density profile through the chimney with different collector radius values.....	91
Figure 5.50: Numerical prediction of the temperature profile through the chimney with different values of roof height.....	92
Figure 5.51.: Numerical prediction of the velocity profile through the chimney with different values of roof heights.....	93
Figure 5.52.: Numerical prediction of the density profile through the chimney with different values of roof heights.....	94
Figure A.1: Actuator Disc Concept [25].....	103
Figure A.2: Stream Tube Defined By Actuator Disc [25].....	104
Figure A.3: Coefficients of Power and Thrust vs. Axial Induction Factor [25].....	107
Figure A.4: Path of a particle of air traveling through the rotor disc, subject to tangential moment.....	108
Figure A.5: Development of tangential velocity in rotor disc (Thickness).....	108

Table of content:

Table 2.1: Models have been used on the dynamic similarity [25].....	28
--	----

NOMENCLATURE & ABBREVIATIONS

2-D, 3-D	Two-dimensional, Three-dimensional
A	Axial interference factor
A	Constants for polynomial approximation
BEM	Blade Element Momentum
C_P	Power coefficient
C	Specific heat of air ($J/(kg \cdot K)$)
CFD	Computational Fluid Dynamics
D, R	Rotor diameter, rotor radius (m)
F	Viscous damping factor
g	Acceleration due to gravity (m/s^2)
HAWT	Horizontal Axis Wind Turbine
k	Thermal conductivity of air ($W \cdot m^{-1} \cdot K^{-1}$)
L	Length of enclosure in meter (m)
MRF	Moving Reference Frame
M	Shaft mechanical moment (N. m)
Nu	Nussult number of air
Pr	Prandtl number of air
P	Shaft mechanical power (Watt)
QUICK	Quadratic Upwind Interpolation for Convective Kinetics
q	Heat flux (W/m^2)
Ra	Rayleigh number of air
RANS	Reynolds Averaged Navier-Stokes
S-A	Spalart-Allmaras (Turbulence model)
SIMPLE	Semi-Implicit Method for Pressure Lined Equations
SST	Shear Stress Transport
T	<i>Temperature in Kelvin (K)</i>
t	Time (sec)
u_i	Velocity components (m/s)

u	Velocity in x-axis (m/s)
v	Velocity in y-axis (m/s)
x,y	Coordinates along x-axis and y-axis

Greek symbols

α	Thermal diffusivity (m^2/s)
β	Thermal coefficient of expansion
γ	Kinematic viscosity of air (m^2/s)
ρ	Density of air (kg/m^3)
μ	Dynamic viscosity of air ($\text{kg}/\text{m} \cdot \text{s}$)
τ	Shear stress at the wall
η	Slip coefficient
λ	Mean free path
s	Momentum accommodation coefficient

Subscripts

m	Mean
h	Hot
c	Cold
s	Slip.

Abstract

This thesis has been conducted to discuss the power generation from renewable resources, hence the energy is very important; and the demand of the energy around the world is increasing specially in our country that's why we are facing a shortage in power. Therefore this thesis has been submitted as a proposal to overcome the shortage of power that could be very useful for our country.

There are many renewable energy sources; such as wind, ocean waves, solar flux, and biomass, which offer emissions-free production of electricity and heat. This thesis has been discussed two different kind of renewable energy system, these are the wind power energy which the simulation of horizontal axis wind turbine (HAWT) has been performed, and the second is the solar energy which the solar chimney system has been modeled as well. Both system are very valuable and suitable to Egypt weather where the sources of wind and solar are available over the year.

First is about utilization of wind energy, which the aerodynamics of HAWT are investigated using CFD simulation package that has been used to solve 3-D turbulent-steady incompressible flow, using the $k-\omega$ SST turbulence models, The aim of this work is to get a better understanding of HAWT aerodynamic mechanisms governing the energy conversion process. Modeling of such system has presented many difficulties due to complex of geometry and huge size of the domain that has been used in order to simulate this kind of turbine. However many aspects have been investigated and power curve has been obtained, blade element method (BEM) used to validate the model, the two results found are highly matched together.

Second is about utilization of the solar energy; which is concerned about the overview of the main characteristics of the solar chimney power plant. It is a technology of electric power generation using solar energy by employing the principle that when air is heated it rises. The created updraft can be used to rotate a turbine placed at an appropriate position within a tall chimney to generate electricity. Discussion has been conducted of these principles and characteristics of the solar chimney, and its requirements.

The solar chimney power plant is considered as an artificial device for wind generation, it is a natural draft device which provides an upward momentum to the in-flowing air; first by converting solar energy into thermal energy in the solar collector. Second the generated thermal energy is converted into kinetic energy in the chimney and ultimately into electric energy using a combination of a wind turbine and a generator.

The technologies for the SCPP (solar chimney power plant) are very simple and reliable, therefore this technology is accessible for the less developed countries, which have limited raw material resources. Furthermore, using large scale of the solar chimney power plant will lead to higher conversion efficiency and is leading to reduction in the energy cost. The objective of this thesis is to analyse the effect of some parameters such as solar radiation, chimney height, and collector radius on the power output of solar chimney power plants. CFD model has been developed for the solar chimney power plant, the simulation package has been used to investigate the selected model.