Experimental, Numerical Simulation and Mathematical Modelling of Vane type Vertical Axis Wind Turbine

by

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LIST OF ABBREVIATIONS

CFD	Computational fluid dynamics
DMST	Multiple streamtube model
HAWT	Horizontal axis wind turbine
SIMPLE	Semi-Implicit method for pressure-linked equation
SST	Shear Stress Transport
VAWT	Vertical axis wind turbine
VVAWT	Vane type vertical axis wind turbine

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LIST OF SYMBOLS

A	Area	m^2
A_s	Swept area	m^2
b	Blade arm dimension	m
c	Blade width	m
Cp	Power coefficient	
$\mathrm{C_p}$	Coefficient of pressure	
C_t	Torque coefficient	
C_D	Coefficient of drag	kg/s
C_{Dsh}	Coefficient of drag under wind shadow effect	kg/s
D	Turbine diameter or width of the wind turbine	m
D_ω	Cross-diffusion term	
E	Kinetic energy	$\mathrm{m}^2/\mathrm{s}^2$
F_D	Drag force	N
F_{Dsh}	Drag force under wind shadow effect	N
f	Damping function in pressure strain tenser	
G_k	Generation of (k)	
G_ω	Generation of (ω)	
H	High of the turbine rotor	m
k	Turbulent kinetic energy	
N	Number of rotation	RPM
N_t	Gear box efficiency	

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N_g	Generator efficiency	
P	Pressure	N/m^2
ΔP	Pressure difference	N/m^2
Re	Reynolds number	
R_t	Turbulent Reynold number	
R	Turbine rotor radius	m
S_k	Source term of (k)	
S_ω	Source term of (ω)	
T	Torque	N.m
t	Time	s
U	Mean velocity components	m/s
$\overline{U}$	Time- averaged velocity in x_i – direction	m/s
V	Wind speed	m/s
X_i	x- direction	
W	power output	W
W_e	Power produce by electrical generator	W
W_m	Mechanical power output	W
W_{sh}	Width of wind shadow	m
W_t	Turbine power output	W
W_{wind}	Kinetic power produce by wind turbine	W
Y_k	Dissipation of (k)	
Y_ω	Dissipation of (ω)	

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LIST OF NOMENCLATURE

β	Angular position between turbine blades	Deg.
γ	Angular position for the first blade	Deg.
Ʈ	Mass-averaged viscous stress tensor	
θ	Angle between frames	Deg.
λ	Tip speed ratio	
μ	Kinetic viscosity	$N.s/m^2$
μ_t	Turbulent eddy viscosity	$N.s/m^2$
ω	Specific turbulent dissipation rate	
ρ	Density	kg/m^3
ω_t	Angular speed of the rotating turbine	rad/s
η	Over all wind turbine efficiency	
α_o	Initial angular position for the second blade	Deg.
α_1	Angular position for the second blade	Deg.
σ_k	Model constant	
σ_ω	Model consta	

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Model dan Simulasi Untuk Reka Bentuk Turbin Angin Paksi Menegak

ABSTRAK

Ekonomi global semasa mencadangkan penggunaan tenaga sumber-sumber yang boleh diperbaharui seperti suria, angin dan biomass untuk menghasilkan kuasa yang diperlukan. Tenaga boleh diperbaharui ialah tenaga alternatif yang bersih, tidak toksik, dan mudah didapati. Teknologi berkaitan tenaga angin telah menyaksikan pertumbuhan yang pesat di seluruh dunia. Turbin angin adalah peranti tipikal yang menukar tenaga kinetik angin ke elektrik. Penyelidikan lalu telah membuktikan bahawa turbin angin paksi menegak (VAWT) menghasilkan kuasa yang lebih tinggi daripada turbin angin paksi mendatar (HAWT). Dalam kajian ini, turbin angin paksi menegak, VVAWT dengan dua rotor yang berbeza (tiga atau empat bilah), yang mempunyai bilah-bilah alih, akan dikaji prestasinya. Model akan dibangunkan daripada bahan ringan dan setiap aspek kira untuk memastikan bilah-bilah ini dapat menahan kelajuan tiupan angin. Di samping itu, saiznya ditetapkan mengikut dimensi terowong angin kelajuan rendah yang terdapat di Universiti Malaysia Perlis. Eksperimen dan simulasi dijalankan bagi plat rata untuk mendapatkan pekali seret dan dibandingkan dengan keputusan yang terdapat dalam kajian. Eksperimen dan simulasi dijalankan untuk model bilah tunggal (dengan bilah-bilah tertutup dan terbuka) dan dua bilah (dengan bilah-bilah terbuka sahaja) yang mempunyai sudut berbeza antara bilah-bilah ini untuk mewakili turbin tiga dan empat bilah. Kajian simulasi tiga dimensi dijalankan untuk meramal ciri-ciri aerodinamik bagi model semasa, menggunakan perisian komersil Dinamik Bendalir Komputeran (CFD) - SolidWork2013, GAMBIT dan FLUENT. Dalam tegasan ricih pengangkutan (SST), model pergolakan k-ω adalah lebih baik daripada model pergolakan lain, seperti yang disarankan oleh beberapa penyelidik. Medan aliran disimulasi pada kelajuan masuk yang tetap. Model matematik dihasilkan untuk mengira keluasan kesan bayang-bayang bilah-bilah turbin ini di bawah kesan bayangan angin supaya diketahui pekali seret untuk tiga dan empat bilah VVAWT yang digunakan untuk pengiraan tork dan kuasa turbin. Untuk tujuan pengiraan tork di bawah kesan bayang-bayang angin, eksperimen dan penyiasatan simulasi dijalankan bagi tiga dan empat bilah VVAWT di kedudukan sudut bilah tetap pada kelajuan aliran udara huluan yang berbeza. Eksperimen juga dijalankan bagi tiga dan empat bilah yang menggunakan transmisi gear dan penjana elektrik untuk mendapatkan output kuasa penjana elektrik. Keputusan ujian digunakan untuk mengesahkan keputusan simulasi dan matematik. Keputusan dibentangkan dalam bentuk pekali seret, bilangan revolusi per minit (RPM). Adalah didapati bahawa nilai bagi turbin empat bilah adalah lebih tinggi daripada turbin tiga bilah bagi halaju aliran udara huluan yang sama. Keputusan juga diberikan dalam bentuk kuasa pekali C_P dan petua λ nisbah kelajuan. Bagi model turbin tiga bilah dengan bilah-bilah yang terbuka, C_P maksimum adalah 0.121 pada 20.6 m/s halaju huluan dan pada λ bersamaan 0.2511. Manakala bagi model turbin empat bilah dengan bilah-bilah terbuka, C_P maksimum adalah 0.237 iaitu 20.6 m/s halaju huluan dan pada λ bersamaan 0.2663. Adalah didapati bahawa turbin empat bilah VVAWT adalah 51% lebih cekap berbanding dengan turbin tiga bilah VVAWT.

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Modeling and Numerical Simulation for the Vane Designs Vertical Axis Wind Turbine

ABSTRACT

The present global energy economy suggests the use of renewable sources such as solar, wind and biomass to produce the required power. Renewable energy is an alternative energy, which is a clean, nontoxic energy source that is available in abundance. Technology related to wind energy has seen a rapid growth worldwide. Wind turbines are typical devices that convert the kinetic energy of wind into electricity. Researches in the past have proved that Vertical Axis Wind Turbines (VAWTs) produce higher power than the Horizontal Axis Wind Turbines (HAWTs). In the present work the Vane type Vertical Axis Wind Turbine, VVAWT, with two different rotors (three and four blades) having movable vanes are investigated in terms of performance. The models are made of light material and every care is taken to ensure that the blades withstand high wind velocities. The sizes of the blades are constrained by the dimensions of the low speed wind tunnel available at University Malaysia Perlis. Experimental and numerical works are carried out for a flat plate to obtain its coefficient of drag, and the results are compared to the results available in the literature. Then, experimental and numerical investigations are carried out for three- and four-blade VVAWT at fixed blade angular positions and for different upstream air flow velocities. The three dimensional numerical investigations are carried out to predict the aerodynamics characteristic of the current models, using commercially available computational fluid dynamic (CFD) software - SolidWork2013, GAMBIT and FLUENT. The Shear Stress Transport (SST), k-ω turbulence model is used, which is better than other turbulence models available, as suggested by some researchers. The flow field is simulated numerically at a fixed inlet velocity. Mathematical models are developed to calculate the shadow area of the turbine blades under the effect of wind shadow to gauge the coefficient of drag for three- and four-blade VVAWT. These are then used in the calculation of torque and the power of the turbine. For torque calculations under wind shadow effect, experimental and numerical works are carried out for models of single blade (with closed and open vanes) and two blades (with open vanes only) having different angles between the blades to represent three- and four-blade VVAWT. Experimental works are also carried out for three and four blades using transmission gear and electrical generator to measure the electrical generator power output. Experimental results are used to validate numerical and mathematical results. The results are presented in the form of a drag coefficient, torque and the number of revolutions per minute (RPM). It is found that the values for the four-blade turbine are higher than that of three-blade turbine for the same upstream air flow velocities. The results are also presented in the form of power coefficient C_P and tip speed ratio λ. It is found that for the three-blade turbine model with open vanes, the maximum C_P is 0.121 at 20.6 m/s upstream air flow velocity and at λ equal to 0.2511. For the four-blade turbine model with open vanes, the maximum C_P is 0.237 at 20.6 m/s upstream air flow velocity and at λ equal to 0.2663. It is found that the four- blade VVAWT is 51 % more efficient than the three-blade VVAWT.

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CHAPTER 1

INTRODUCTION

1.1 Background

The basic necessities for sustaining economic development for fast growing population in any country are energy and water. It is expected that by 2050, energy demand may double or even triple because of the global population growth and the expansion of developing countries' economies. Therefore, finding sufficient supplies of clean and sustainable energy for the future is the global society's most daunting challenge for the twenty-first century. It is expected that the future will be a mix of energy technologies with renewable sources such as solar, wind and biomass playing an increasingly important role in the new global energy economy (Foster, et al., 2009). The exploration of all aspects of energy production and consumption, including energy efficiency and clean energy, is urgently required.

Since approximately 200 years ago, the world has begun dependence on fossil fuels. The fossil fuel era expanded with the discovery of oil. Due to high demand of energy, more fossil fuels such as coal are burnt, resulting in CO_2 emission into the atmosphere. The global climate has somewhat changed because of the emission of CO_2 into the atmosphere. This is normally referred to as global warming. Developed nations solve this problem by investing heavily in renewable energy sources. As it is, there are only a few non-renewable energy sources in the world, and the energy from these sources drain very fast due to rapidly growing demands. Alternative energy in the form of

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renewable energy has to be found in order to address the energy issues of the future. The world hopes for a sustainable future, and hence a renewable energy revolution is needed. A sustainable future belongs to sources of clean energy and to those who prepare for it right now.

1.2 Renewable Energy

Energy can be divided into two types, namely non-renewable energy and renewable energy. Non-renewable energy does not regenerate itself at a sufficient rate for sustainable economic extraction in the human timescale. Examples of the sources of this type of energy include petroleum, natural gasoline, coal and nuclear energy. Unfortunately, these carry many issues. For example, harnessing nuclear energy is highly risky, while traditional fossil fuels are very quickly depleting. The world needs to find substitutes for these energy sources, which should be pollution free and abundantly available. Therefore, the attention concentrated on non-renewable energy sources has now shifted to renewable energy sources, particularly efficient renewable energy sources.

Renewable energy is energy that comes from sources that are naturally renewing itself on a human timescale. Examples of renewable energy are wind energy, solar energy, tidal energy, geothermal energy, gravitational energy and biomass energy. Renewable energy is an alternative energy that is clean, nontoxic and abundantly available in nature. The strategy of many nations is to supply energy from renewable sources, especially when there are numerous environmental sustainability concerns that must be addressed appropriately (Johnson, 2006).

There are many advantages of using renewable energy, such as sustainability (cannot be depleted), ubiquity (found everywhere across the world in contrast to

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fossil fuels and minerals), generally non-polluting and carbon free. Non-renewable energy sources can be acquired from almost all over the world, which is in contrast to fossil fuels and minerals. Non-renewable energy is also environmental friendly as it does not contaminate its surroundings. For wind energy, it does not need water in the production of electricity, and this gives much advantage in dry areas across the world, such as at the southwest and most of the west of the United States of America (Nelson & Starcher, 2015).

However, there are also disadvantages of renewable energy, including its variability, low density, and generally higher initial cost. To add, renewable energy sources may cause visual pollution, odor (from biomass), perceived avian issues (for wind plants), and large land requirements (for solar plants) (Foster et al., 2009).

1.3 Wind Energy

Wind energy has been utilized for at least 3000 years for sailing ships, milling grains and pumping water. Wind is produced because of the uneven solar heating of the earth's land and sea surfaces. The first vertical axis windmill in 644 AD had sails connected to a vertical shaft connected to a grinding stone for milling purposes. In the middle ages, the post-mill was first invented in Europe, and this was independent from the vertical-axis wind wheels of the Orient.

Among all available renewable energy sources, wind energy has the advantage of being available in abundance, clean, and inexhaustible. It has no contribution to global warming, and it requires less installation and maintenance cost for power generation (Foster et al., 2009). With the first oil price shock in the early 1970s, interest in wind power reemerged. Providing electrical energy from the wind has now become important

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