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As a conclusion of the experimental work, two and four-bladed turbine rotors were tested including all previous parameters. It was found that the four-bladed wind turbine is the most efficient one.

For the theoretical work, the blade element theory was applied using a power coefficient formula which was obtained from the application of both angular momentum equation and blade aerodynamics. The obtained analysis showed that the maximum power coefficient was in the neighbourhood of 0.43. However, the corresponding obtained experimental value was about 0.35.

Finally, it may be concluded that within the tested range the four-bladed rotor having blade profile of NACA 4418 or FX 60-126, chord length of 150mm gives the best performance when the blade setting angle ranges from five to twenty degrees and the rotor to hub diameter ratios are in the range between 5.5 and 6.5 .

الملخص

تناولت الرسالة كلا من الدراستين العملية والنظرية على تربين هوائي أفقي المحور . ولقد صمم التربين لدراسة تأثير كل من المتغيرات الآتية : طول وتر ريشة التربين ، طول الريشة ، زاوية ميل الريشة على اتجاه السريان وذلك لثلاثة أنواع مختلفة من الأرياش . كما شملت الدراسة بيان تأثير عدد الأرياش على أداء التربين . وقد أجريت جميع هذه الاختبارات عند مخرج نفق هوائي صمم لهذا الغرض .

ولقد بيّنت الدراسة أنه باختبار ثلاثة أطوال مختلفة لوتر ريشة التربين وهي ٥٠مم ، ١٠٠ ، ١٥٠مم فان أفضل أداء للتربين يكون لطول وتر يساوى ١٥٠مم . كما بيّنت الدراسة أنه باختبار ستة أطوال مختلفة للريشة ممثلة بالنسبة بين القطر الخارجي وقطر السرّة لمروحة التربين والتى تراوحت بين ٤ ، ٧ فان أفضل نسبة أداء تقع بين ٥ر٥ ، ٦ر٥ .

وبالنسبة الى بيان تأثير زاوية ميل الريشة على اتجاه السريان والتى أمكن تغييرها من صفر الى ٣٠ درجة فان أحسن أداء يحدث عند زوايا ميل تتراوح بين ٥ درجات ، ٢٠ درجة .

ولبيان تأثير أنواع الأرياش على الأداء ، فقد اختبرت ثلاثة أنواع مختلفة وهى NACA 0012 ، NACA 4418 ، FX 60-126 ، ووجد النوعان الآخران أفضلها أداء .

ولجميع المتغيرات السالفة الذكر فقد بيّنت الاختبارات أن التربين الهوائى ذا الأربعة أرياش أفضل أداء من نظيره ذى المريشتين .

وبالنسبة للدراسة النظرية فقد طبقت نظرية شريحة الريشة مع استخدام كل من معادلة كمية الحركة الزاوية ومعادلات الديناميكا الهوائية للأرياش ، ووجد أن أقصى معامل قدرة للتربين حوالى ٤٩ر٠ بينما نظيره بالدراسة التجريبية حوالى ٣٥ر٠ .

../.

وختامـــا لهذا البحـــث فانه يمكن تلخيص النتائج كما يلـــى :

(١) التربين الهوائى ذو الأربعة أرياش أفضل أداء من نظيره ذى الريشتين وذلك لكل من النوعين : NACA 4418, FX 60-126.

(٢) أفضل أداء لطول وتر ريشـــة التربين مســـاو ١٥٠ مم .

(٣) أفضل زوايا ميل للريشة على اتجاه السريان تتراوح بين ٥ ، ٢٠ درجة.

(٤) أحســـن أداء للنســـب المختبرة بين القطر الخارجى وقطر الصـــرّة تتراوح بين ٤ ، ٧ وهى النســـب التى تقع بين ٥ر٥ ، ٥ر٦ .

العنوان:	Investigation of the Effect of some Design Parameters on the Performance of Wind Turbines
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g :	Acceleration.	m/S^2
l :	Blade length.	m
i :	Incidence angle.	Degree
I :	Angle of inclination.	Degree
K:	Velocity coefficent.	
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ω	: Angular velocity.	rad/s
ρ	: Air density.	Kg/m^3
α	: Blade setting angle.	degree
τ	: Torque.	N.m
λ	: Tip speed ratio.	
λ_m	: Maximum tip speed ratio.	
δ	: The blade solidity.	

AIN SHAMS UNIVERSITY

FACULTY OF ENGINEERING

INVESTIGATION OF THE EFFECT OF SOME DESIGN PARAMETERS ON THE PERFORMANCE OF WIND TURBINES

BY

ENG. ASHRAF ABD EL-BADEE M. GHORAP

A Thesis

submitted in partial fulfillment for the requirements of the degree of master of science in Mechanical Engineering (energy).

UNDER THE SUPERVISION OF

PROF. Dr. A.M. EL-SIBAIE

Dr. M.I.GOHAR Dr.R.N. ABD EL-MESSIH

1990

EXAMINATION COMMITTEE

EXAMINERS

1- PROFESSOR Dr. SAMI MIKHAIL.

2- PROFESSOR Dr. K. SH. KADDAH.

3- PROFESSOR Dr. A.M.EL-SIBAIE.

TO

MY PARENTS

MY SISTERS

FOR THEIR LOVE

AND HELP

PREFACE

This thesis is submitted to Ain shams university for the degree of master in mechanical engineering. The work included in this thesis was carried out by the author at the laboratory of fluid mechanics, Energy and automotive depart ment Faculty of engineering, Ain shams university.

Name:
Eng. Ashraf abd el-badee ghorap .

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Appreciation is also extended to all those who faithfully helped and encouraged me to carry out this work.

Hoping that this research will be useful for the developing countries and our beloved country, EGYPT.

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Experimental and theoretical investigations were performed on a specially designed horizontal axis wind turbine. The experimental work was carried out near the exit of a wind tunnel. This tunnel was designed for testing wind turbines.

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INTRODUCTION

Nowadays, new sources of energy are searched for, because of the deficiency in the traditional energy sources as petroleum, natural gas and coke.

Renewable energy is the term used to cover those continuous energy flows that occur naturally and repeatedly in the environment. Energy from the sun, wind and tidal waves are some sources of such energy. The heat from within the earth itself (geothermal energy) is also usually regarded as a renewable energy source since in total it is a source on a vast scale; although locally it cannot always sustain continous extraction.

As for wind energy, power can extracted by using wind turbines or aerogenerators. As air flows over the turbine blades, it creates a turning force on the rotor assembly which can then be used either to drive water pumps or more conveniently to generate electricity.

The fundamental questions to be answered concerning windmill location are:-

1- Optimum geographical placement.

2- Variation of wind speed with height.

3- Wind speed variation with time; and knowledge of maximum winds to avoid excessive stresses.

For geographical placement, long-term data are requried over large regions to determine which areas of a country are most appropriate for wind power generation.

The height of a windmill must be decided on essentially economic terms since the simplest noneconomic arguments indicate that the heigher tower is the better. Theoretically the wind blows from high-pressure zones to low-pressure ones. However, at medium & high altitudes, its direction is modified by the earth's rotation.

Variations of the mean wind speed with time must be considered for daily, monthly, yearly, and long term periods. The annual duration of calm spells is important because it indicates the period which must be covered by storage when small or medium-sized wind-driven plants are used.

As for the wind turbine itself, there two main types depending on the axis of rotation. The first type is the horizontal axis in which the rotor shaft is in a horizontal position. The rotor may be single, double or multibladed. The second type is the vertical axis wind turbines in wich the rotating shaft is in an axial vertical position. This type contains many turbine configurations and kinds, as Darrieus, Savonious, and Lafond wind turbines.

In the present work a horizontal axis wind turbine was designed and tested to investigate the effect of some design parameters on the turbine performance. The parameters investigated are the untwisted blade chord length, the ratio between rotor and hub diameters, the blade setting angle and the blade profile. Moreover, the effect of the number of turbine blades was also studied. The tests were carried out using a specially designed wind tunnel.

The theoretical turbine performance was also studied by applying the blade element theory and using a power coefficient formula which was obtained from the application of both angular momentum equation and blade aerodynamics. A comparison was made between experimental and theoretical results indicating the same trend.

CHAPTER 1

CHAPTER (1)

REVIEW OF THE PREVIOUS WORK

1.1) General.

The use of wind turbines goes back for over 2000 years ago. Recent studies have confirmed that the horizontal-axis machine is a superior solution for better efficiency and minimum cost ; especially in the size range over 100 Kw.

In strong winds, several wind turbine operators have recently reported experimental measurements of power and thrust which is higher than theoretical predictions. One possible reason for these discrepancies is that, aerofoil lift is higher than that anticipated in the post-stall region due to the existance of span wise flow components. Flow visualisation studies on fans support this hypothesis as shown in figure (1.1). A critical evaluation of experimental data from a number of sources for both model and full scale, has therfore been made and clear indications of high post-

Fig (1.1) Flow visualization on a rotating fan blade stall lift are presented.

1.2) The effect of rotation on aerofoil characteristics.

Some conclusions, by previous investigators, based on the studies of the effect of rotation on aerofoil characteristics may be summarised as follows :

a) By using surface pressure measurements, D.J.Milborrow (7) mentioned that, Himmelskamp obtained the following results : Maximum lift coefficents increase towards the blade root and drag coefficents also increase at angles of attack above 5 degrees.

b) There are discrepancies between theory and measurements at low tip speed ratios. Reference (7) mentioned also that Viterna and Janetzke's analysis of data from the 38 m MOD-0 machine led them to conclude : There was a slight increase in the maximum lift, which then fell below the two dimensional value at angles of attack (α) above 20. Drag coefficents were roughly halved for ($20<\alpha<50$).

c) Theoretical approaches, using stalled flat plate theory, and taking account of the finite aspect ratio of rotor blades predict a reduction of both lift and drag. However, Milborrow (7) mentioned that, Hilbs and Radkey found it necessary to make further modifications in the "shallow stall" regon ($10<\alpha<25$) to obtain agreement with measured powers.

d) Stall is likely to be delayed by radial flows. In addition, D.J.Milborrow (7) stated the following conclusions:

1- There are considerable variations in tabulations of aerofoil data for blade sections, even when conditions are nominally identical and considerable care must be taken in the selection of data sets.

2- It is known that roughness regardes aerofoil characteristics and turbulence enhances them. However, there are again variations in the puplished data.

3- It follows that some indications of performance enhancement can possibly be ascribed to the turbelent conditions in which wind turbines operate.

4- Strong evidence of the existance of radial flows comes from flow visualisation studies, measurements of rotor loades and power, detailed measurements at the rotor plane and also from theoretical considerations.

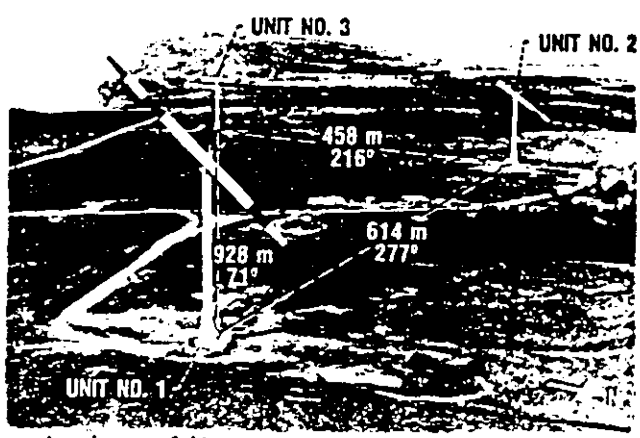
5- The efects of radial flows can also be explained at least in part, by known features of yawed flows.

6- Drag coefficients are reduced below the two dimensional values when stall is delayed and, post stall is reduced to reflect the aspect ratio of the blade section.

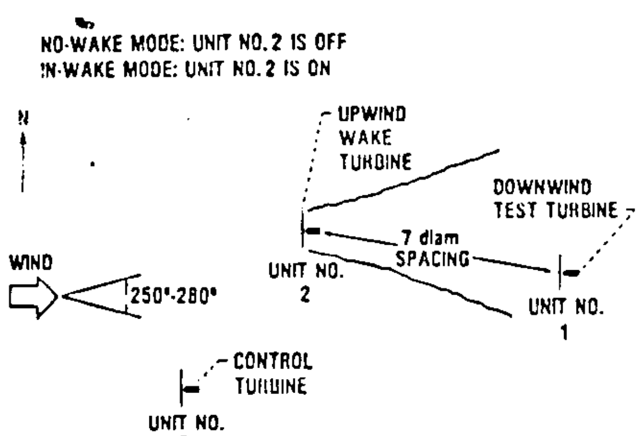
1.3) The wake effect.

Neusadter (8) presented a method of testing the performance of a cluster of wind turbine units. Data analysis equations are drived from a simple and direct procedure for determining the reduction in energy output caused by the wake of an upwind turbine. This method appears to solve the problems presented by data scatter and wind variability.

His proposed use of an undistubed wind turbine, as the experiment control unit and of cumulative energy, as the measured performance parameter, greatly simplified the analysis. He has also presented a sample case to illustrate the proposed method for evaluating wake effects on performance. The results for this case indicate that at an inter unit spacing of seven diameters, wind turbines shown in figs (1.2) and (1.3) will experience a decrease in energy



Fig(1.2) General view of the Goldendale, wind turbines showing the nonuniform spacing of the three[2.5] MW units.



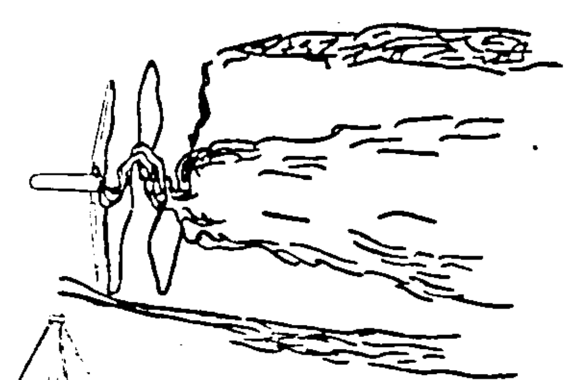
Fig(1.3) Shematic plan view of the Goldendale site showing operating conditions during wake effect tests.

output of about 10 % when operated in the wake of an upwind unit.

This study was limited to a relatively simple case of wake interaction between only two turbines, in which one turbine was operated completely within the wake of the other. No measurements were made of other effects which could be significant, such as partial wakes and atmospheric stability.

Afjeh et al (10), based on the assumption that wake geometry of a horizontal axis wind turbine closely resembles that of a horizontal axis wind turbine closely resembles that of a hovering helicopter, presented a method for predicting the performance of a horizontal axis wind turbine. A vortex method was used in which the wake is composed of an intense tip- vortex and a diffused wake.

Because of the complex nature of the flow field in which horizontal axis wind turbines must function, determination of the aerodynamic performance can be quite difficult. Fig. (1.4) shows a flow pattern of a full scale wind turbine.



Fig(1.4) Flow Pattern of a full scale wind turbine operating under low power generation conditions.

1.4) The performance of wind turbines.

Methods concerned with the prediction of aerodynamic loading and performance of wind turbines have been reviewed in a number of places. In general, these methods have been developed by modifing coventional propeller and /or helicoter theories. Classification of the methods is based on the manner in which the induced velocity at a blade section is evaluated.

Simple blade element - momentum theories (strip theories) replace the rotor with an actuator disk having an infinite number of blades. The induced velocity at a blade section is evaluated from stream tube momentum considerations assuming the flow to be planar or without swirl. All blade sections are assumed to operate independently of each other. However, it has been found that an emperical correction to the methods was required for computations when the wind turbine operation in the vortex ring state.

Analysis, by either blade - element / momentum theory or by vortex theory, revales that the induced velocity far down stream of the rotor differs from that at the rotor disc. Consequently, the blade wake size must change (expand or contract) depending on the sign of the induced velocity. On the other hand, if the free stream velocity, which is the primary factor in establishing the mass flow rate into the wake, is high, wake deformation effects are negligible.

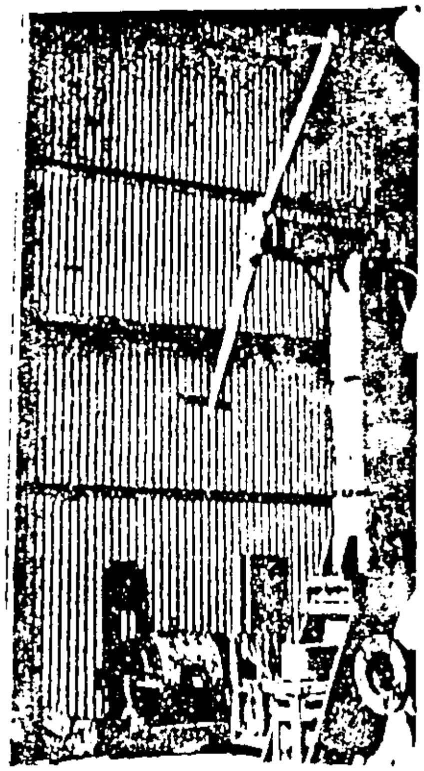
Comparison of the results of a free wake analysis with several models reveals that accurate results can be obtained, for operating conditions considered, with substntial savings of computer time.

1.5) The effect of profile drag on induced velocities.

A discussion concerning the effect of profile drag on induced velocities was presented by Galetuse (14) who concluded that Glauert's relations for the ideal wind mill are also valid for a real one. Using these results, the optimum conditons for induced efficency and power coefficient are obtained.

1.6) Experimental results related to tip vane augmenters.

The concept of fitting lifting surfaces (tip vane augmenters) to the rotor tip of horizontal axis wind turbines, was discussed by GARSIDE (12). He mentioned that Van Holten conceivd the tip vane concept or blade tip mounted lifting surfaces which rotate in the plane of a wind turbine rotor, thus inducing additional air mass flow into the disc of a rotor. Garside provided also a dimensional data for two types of tip vanes and showed the design of a new rotor unit having tip vanes to be fitted to a 2 meters diameter model turbine. The unit has been tested in the large open jet wind tunnel shown in figure (1.5). Air flow augmentation was

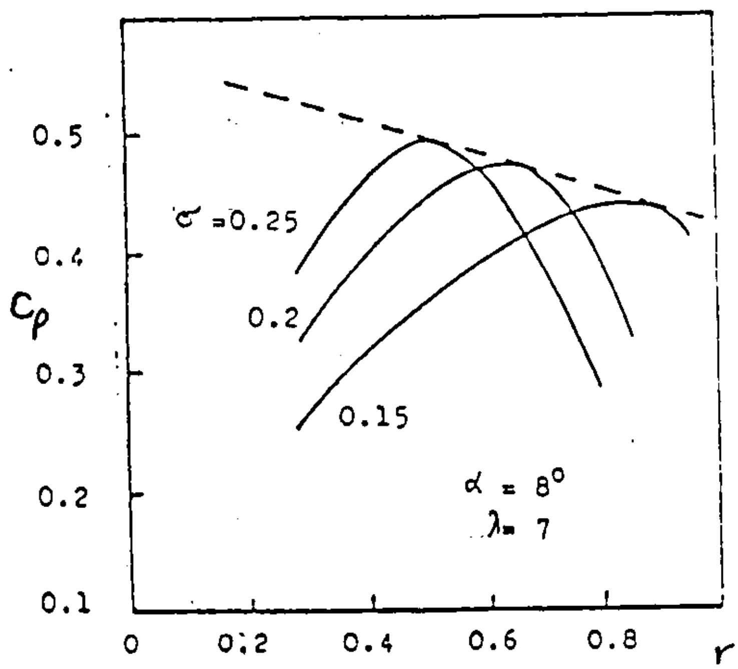


Fig(1.5) View of the test turbine fitted with tip vane augmenters.

confirmed using helium filled bubbles for visualisation. A tunnel speed restriction may have masked better results.

1.7) The effect of blade twist on turbine performance.

The effects of blade twist and blade chord variation with the radius were studied by Khalafallah etal (15). They had proved that the simple constant chord - untwisted blade rotors have power coefficient less by 26 percent than the maximum possible values. The non- constant chord - segmented blade rotors have a better performance and their maximum power coefficent is only ten percent less than that of the fully twisted blades. Figures from (1.6) to (1.10) show the results which they obtained.



Fig(1.6) Distribution of local power coefficient (Constant chord blades)

Hence, the use of segmented - non constant chord blades may be of great advantage for small power turbines as this

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" بسم الله الرحمن الرحيم "

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فى الهندسة الميكانيكيه (طاقـة) مـــــــن
قسم هندسة الطاقة والسيارات

عنـــــــوان الرسالـــــة

" دراسة تأثير بعض عناصر التصميم على اداء التربينات الهـــــــــــوائية "

اسم الباحـــــــث

المهندس / اشرف عبد البديع محمد غـــــــراب

اسماء السادة المشرفـــــــــــين

١ - أ.د. أحمد محمد السباعـــــــــى
٢ - د. محمـــــد اسماعيـــل جوهـــــــر
٣ - د. رؤوف نصــــــــيف عبد المســيح