ON THE AERODYNAMIC PERFORMANCE OF DARRIEUS WIND ROTOR

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الملخص

تتسم المروحة الهوائية نوع Darrieus بجملة من الميزات عندما تكون صغيرة الحجم نسبياً ومستقلة عن الشبكة الكهربائية. وحيث إن الدوار يعتبر المسؤول الرئيس عن إستخلاص طاقة الحركة الكامنة في الريح، عليه فإنه من المنتظر بكل تأكيد أن يكون لخصائص الشكل الهندسي لهذا الدوار أثر ملحوظ على أدائه وبالتالي على أداء المروحة بوجه عام. وقد تم في إطار هذا البحث دراسة تأثير خصائص الشكل التالية: عدد ريش الدوار، نسبةٍ وتر الريشة إلى نصف قطر الدوار، نسبة الصلادةِ، و نسبة إرتفاع الدوار إلى قطره. كما تم أيضا دراسة تأثير قيمة رقم رينولدز على أداء الدوار. اسُِّست الدراسة علىٍ إستخدام النموذج الرياضي "Multiple Streamtube" و مقطع ريشة من نوع "NACA0012" كما اعدت النتائج النهائية في هيئة مخططات بيانية توضح معامل القدرة كدالة في ما يسمى بالسرعة الطرفية النسبية.

ABSTRACT

Darrieus wind turbines offer a number of advantages for small scale stand-alone applications. With the rotor being the direct means of extracting kinetic energy from the wind, its particular geometry must undoubtedly have a great effect on the overall performance of the turbine. The rotor geometrical parameters that were investigated in this study included: number of blades, chord to radius ratio, solidity and height to radius ratio. Moreover, the effects of Reynolds number were also included. The analysis was based on the use of the well documented multi streamtube mathematical model and NACA0012 rotor-blade profile. Results are presented in the form of power coefficient as function of tip-speed ratio.

KEYWORDS: Darrieus; Wind turbine; Wind rotor; Wind energy.

INTRODUCTION

It is well known that energy has been and still is one of the basic needs for the development of mankind. It is equally well known that use of conventional energy sources such as oil, gas, and coal pollutes the environment and therefore adversely affects human beings and other living organisms. Equally hazardous is the use of nuclear materials as a source of energy. Moreover, all of the above mentioned energy sources are limited in supply and therefore they are bound to be totally consumed in the near future based on the current or projected worldwide demand for energy. By contrast, renewable energy is free, non-pollutant and everlasting. One of the most developed and commercialized sources of renewable energy is wind energy which is used nowadays mainly for production of electricity. This is clearly reflected in the substantial increase in the generated electrical energy each year. For example, the total installed electrical power generated by wind in the European union was about 74767MW by the end of

2009 [1]. It is expected that 20% of the total electrical power generated in the USA will come from wind energy [2].

The wind turbine is the electro-mechanical system which converts the kinetic energy of the wind into electrical energy. As shown in Figure (1), there are basically two main types of wind turbines which may be used for electricity production. The first type is termed "horizontal-axis wind turbine" or "HAWT" in which the wind rotor or blade assembly rotates about an axis which is horizontal with respect to the ground. The second type is termed "vertical-axis wind turbine" or "VAWT" in which the wind rotor rotates about an axis which is vertical with respect to the ground. One of the basic components of the wind turbine of either type is the wind rotor which is responsible for the direct extraction of part of the available wind kinetic energy and converting it into mechanical energy or shaft power. Such power may then be used to run an electric generator. Both types of wind turbines may be designed and built either to work independently of the electrical network or grid, in what is called "stand-alone" mode, or else they may be designed and built to be connected to the electricity network in what is called "grid-connected" mode.

(a) HAWT **(b) VAWT-Darrieus**

Figure 1: Basic Types of Wind Turbines

The wind rotor consists of a number of blades whose shape differs according to the type of wind turbine. In the "HAWT" type, the blades are normally straight, tapered, and twisted. As for the "VAWT" type, the blades may be straight or curved. However they are normally untapered and untwisted. In both types of wind turbine, the geometrical shape of their cross section resembles the cross sectional shape of an airplane wing or what is known as "airfoil". Compared to HAWT, the Darrieus wind turbine is slightly less efficient and can have problems with self starting. However, it offers several advantages such as simplicity of design, better accessibility to the electric generator and lower aerodynamic noise. The purpose of the present study is to investigate the effects of some of the main geometrical design parameters on the performance of the Darrieus wind rotor. It is believed that knowledge of such effects would contribute to a better rotor design and more efficient performance. The geometrical design parameters which have been investigated were the number of rotor blades, blade chord to rotor radius ratio, rotor height to diameter ratio, and rotor solidity. Moreover, the effects of blade-chord Reynolds number have also been included.

GEOMETRICAL DESIGN PARAMETERS OF DARRIEUS ROTOR

In the process of the aerodynamic design of the rotor, several geometrical parameters must be considered in so far as their influence on rotor performance. These parameters are hereby briefly presented.

Curved Blade Vs. Straight Blade

The choice between curved or straight blade probably constitutes the first decision in the design process. As an example, for the same blade length and the same rotor diameter, the straight-bladed rotor has a relatively larger swept area. Thus for the same power coefficient, the straight-blade rotor would produce more power than a curved one. From structural point of view, the bending stress acting on the curved-blade is mostly axial contrary to the case of straight blade. Also it is expected that blade tip losses would be higher in the case of straight-blade rotor.

Rotor Height to Diameter Ratio, (H/R)

Denoting the height and diameter by 2H and 2R respectively, this ratio becomes simply (H/R). Generally speaking, one expects that higher values of this parameter are advantageous for large scale rotors. Because in such case the extended rotor height helps in capturing relatively higher wind velocities while the lower diameter helps in reducing centripetal accelerations thus lowering inertial loads.

Number of Blades, N

A number of the existing large scale Darrieus wind turbines have rotors which consisted of two blades. Because of the cyclic variations of blade angle of attack as the rotor turns, the torque and the magnitude and direction of the resultant aerodynamic force consequently vary cyclically. On the other hand in a three-blade rotor, these cyclic variations are much greatly reduced [3]. Cyclic variations of forces acting on a blade increase the probability of fatigue failure. Moreover, it is shown that a three-blade rotor has higher potential to self start than a two-blade one [4].

Chord to Radius Ratio, (C/R)

Since the blade of the rotor moves in circular path, flow curvature leads to variation of local angle of attack along the chord of the blade cross-section or airfoil. Flow curvature also tends to make the airfoil behave as if it were of different camber distribution. Such effects increase with increasing values of (C/R). Now since lift and drag data, employed in the design and performance analysis, are normally obtained from wind tunnel tests of airfoils, higher margins of error occur with higher values of (C/R).

Rotor Solidity, σ

Solidity is formally defined as the ratio of total planform area of the rotor blades to the rotor swept area. It is common in the literature to use the term (NC/R) to imply σ. Note that while $\sigma=(1/2)(NC/R)$ for a straight- blade rotor, the solidity for curved-blade rotor is shown [5] to be a function of both (NC/R) and (H/R). A rotor with lower value of σ is not only lighter in weight but also runs relatively faster than similar rotor with higher solidity. Per unit of power output, a lighter rotor signifies less material to produce it and hence costs less to build it. Meantime, it is argued that higher values of σ help overcome the rotor self-starting problem.

METHOD OF ANALYSIS

The first mathematical models of Darrieus rotor may be grouped under what is termed blade-element momentum methods, or BEM. The first of such a group was due to Templin [6] who introduced what became to be known as "single streamtube model". He assumed the rotor to be enclosed in a single streamtube and making use of "Glauert actuator disc theory", Templin replaced the wind rotor with an "actuator disc" through which the flow velocity was assumed to be uniform. By equating the axial component of the aerodynamic force acting on the rotor blades with the rate of change of axial momentum across the disc, the air velocity through the rotor was obtained. Given such velocity, it was then possible to compute the torque and power produced by the rotor. Further refinement of this model took place when Wilson and Lissaman [7] and then Strickland [8] proposed what is known as "multi streamtube model". Instead of a single streamtube enclosing the whole rotor, in the new method a series of adjacent aerodynamically independent parallel streamtubes run through the rotor. Again the BEM technique was employed in order to determine the velocity distribution of the air passing through the rotor. When compared with experimental results, this model shows some improvement over the previous model especially in the value of maximum power coefficient. Later on, Paraschivoiu [9] introduced what is termed "double multiple streamtube models". In this model, the flow velocity through the upstream half of the rotor is assumed to be different from that of the downstream half. This implies the use of two actuator discs employed in tandem. Though this model is more accurate than the previous models in so far as the prediction of local aerodynamic blade forces, it nevertheless over predicts power coefficient for high-solidity rotors.

A completely different approach from the previous BEM methods, termed "Vortex model", was proposed by Larsen [10]. In this method, the rotor blade-element is replaced by a "bound" and "trailing" vortices in much the same way as the "vortex-lattice method" employed for airplane wing analysis. The induced velocities resulting from this vortex system are then computed and so are the resultant flow velocity and angle of attack. Consequently the aerodynamic forces and therefore the axial force, torque and power may then be determined. Following the techniques of cascade flow analysis normally employed in the field of turbomachinery, Hirsch and Mandal [11] introduced what is known as "cascade model". In this model the rotor blade-elements are assumed to lie in a plane surface with blade spacing equal to the rotor circumference divided by the number of blades.

Rotor performance results are normally presented in a non-dimensional form which enables the use of such data no matter how large the wind rotor is, provided geometrical similarity between the different-size rotors is maintained. A key performance indicator is the curve of power coefficient, Cp, as a function of what is known as tip speed ratio, λ_0. The tip speed ratio and power coefficient are defined by the following relations:

$$\lambda_\circ = \frac{\omega R}{V_1} \tag{1}$$

$$C_P = \frac{P}{\frac{1}{2}\rho V_1^3 A} \tag{2}$$

where: ω is rotational speed in (rad/s), V_1 is wind speed in (m/s), P is power in (W), ρ is density in (kg/m^3) and A is rotor swept area in (m^2).

In the present study, the multi streamtube model [8] was adopted and implemented in a computer program. The inputs to the program are the rotor height, rotor diameter, number of blades, blade chord, and aerodynamic characteristics of the blade-cross section. The particular rotor blade curvature employed in the program satisfies relations (3) and (4).

$$\left(r/R\right) = \sin\left(\frac{\pi z}{2H}\right) \tag{3}$$

$$\beta = \tan^{-1}\left\{\frac{(2H/R)}{\cos\left(\pi z/2H\right)}\right\} \tag{4}$$

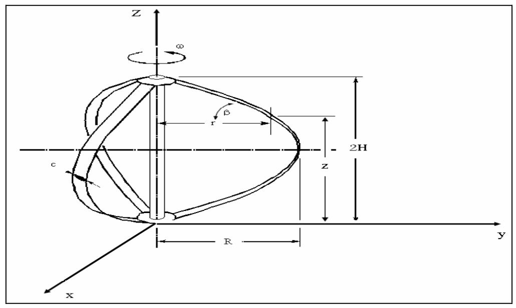

Figure 2: Darriues Geometry

Where: r, z and β are as shown in Figure (2). The output of the program consists of torque and power coefficients as function of tip speed ratio. In order to validate the results obtained from the computer program, a set of experimental data in the form of C_p as a function of λ_0 was employed [8]. Figure (3) presents the results of the above mentioned wind tunnel tests as well as the corresponding theoretical results obtained from the computer program. As can be seen from this figure, very good agreement exists between theoretical and experimental results over most of the λ_0 range.

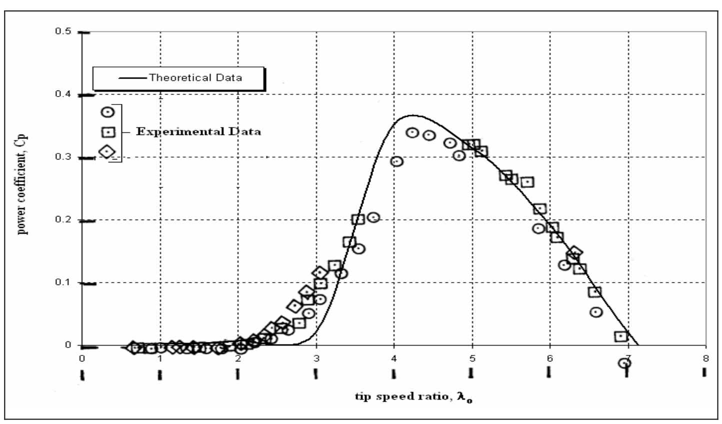

Figure 3: Comparison of computer program results with wind tunnel test results

RESULTS AND DISCUSSION

Within the accuracy of the multi streamtube method employed, the following results pertaining to the influence of the various geometrical parameters on the rotor performance were obtained:

Influence of Number of Blades

At constant values of (H/R) of 1.0 and (C/R) of 0.09, Figure (4) shows that as N increases the maximum value of power coefficient, Cp_m, increases at first then it decreases. It is also noted that the value of λ_0 at which Cp_m occurs shifts towards lower values as N increases indicating thereby a decrease in rotational speed which in turn necessitates higher gear-up ratios. Increasing the number of blades also makes the $Cp(\lambda_0)$ curve more "peaky" which narrows the λ_0-range over which the rotor operates more efficiently. Similar behavior was shown to exist for values of (H/R) of 0.67 and 1.5 [5].

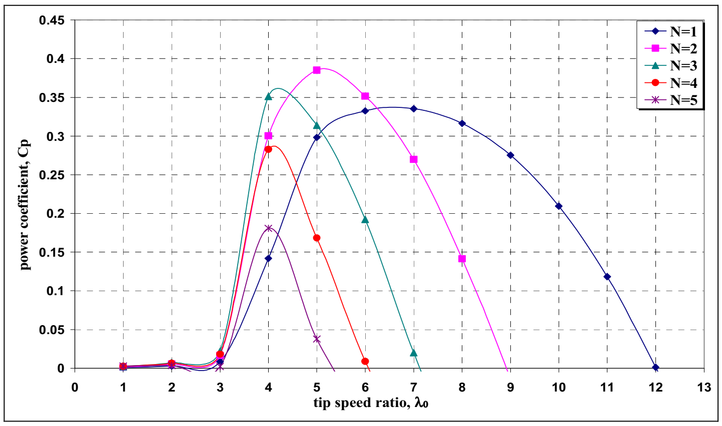

Figure 4: The Effect of Number of Blades on the $Cp(\lambda_0)$ Curve for Constant (C/R) of 0.09 and at (H/R) =1

Influence of Chord to Radius Ratio

As can be seen from Figure (5), the influence of an increase in (C/R) on the $Cp(\lambda_0)$ curve at values of (H/R) of 1.0 and N equal to 3 follows the same trends just observed for the corresponding influence of N. Looking closely, one notices that the curves in Figure (5) coincide with corresponding curves in Figure (4) having the same value of the product (NC/R). This is further illustrated in Figure (6) which shows clearly that for a given value (H/R), the effects of N and (C/R) are identical provided the value of (NC/R) remains fixed. Similar behavior was shown to exist for values of (H/R) of 0.67 and 1.5 [5]. This and the previous result show that for a fixed value of (H/R), it is the combined effects of N and (C/R) rather than the values of N or (C/R) alone which actually determines the shape of the $Cp(\lambda_0)$ curve. However, it is expected in practice that varying N or (C/R) independently while keeping (H/R) and (NC/R) constant would not lead to identical results. For one thing, an increase in the value of C is bound to cause a relative increase in Cp due to the resulting increase in blade Reynolds number as will be explained at the end of this section. On the other hand, increasing N is expected to increase the adverse effects of the wake flow of one blade on the others thus leading to a relative decrease in Cp.

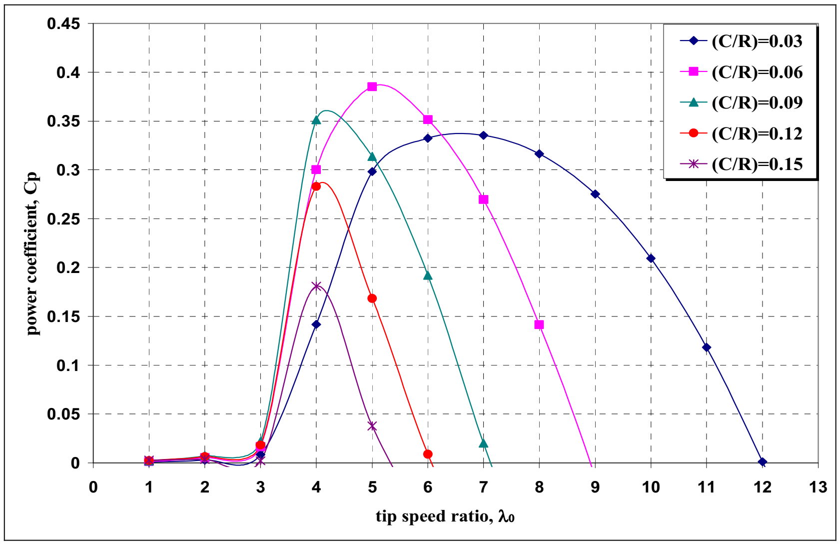

Figure 5: Chord to Radius Ratio Effect on Cp(λ_0) Curve for Constant Number of Blades of 3 and at (H/R) =1.

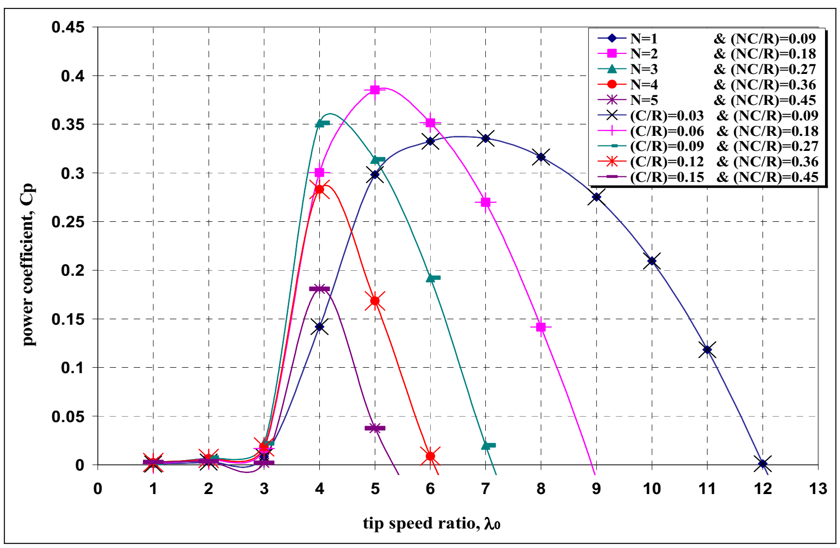

Figure 6: Coincidence of Cp(λ_0) Curves for Pairs of Rotor Configurations with (H/R)=1 and Having Different N or (C/R) but Identical (NC/R).

Influence of Rotor Solidity

By virtue of the relationship between rotor solidity and the term (NC/R) noted earlier, Figure (6) in fact represents exactly the influence of σ on the $Cp(\lambda_0)$ curve since (H/R) was held constant. Therefore, it can be said that a decrease in rotor solidity results in a lighter and faster running rotor.

Influence of Height to Diameter Ratio

Figure (7) presents $Cp(\lambda_0)$ curves for a constant value of (NC/R) of 0.18 and values (H/R) equal to 0.67, 1.0 and 1.5. It can be seen from this figure that as (H/R) increases the value of Cp decreases over the low λ_0-range with mixed but slight changes over the high λ_0-range. It is shown [5] that this decrease persists even for higher values of (NC/R) reaching 0.27 or slightly more. This decrease is mainly due to the fact that as (H/R) increases, the blade angle β increases towards the upper and lower parts of the rotor which in turn leads to an increase in the blade section angle of attack, α. Now since α is known to be relatively high at low values of λ_0, the foregoing additional increase in this angle would undoubtedly lead to flow separation on the blade which in turn would lead to a decrease in Cp. Generally speaking, changing the value of (H/R), results in a change in the swept area. Now since the rotor power is directly proportional to both Cp and A as indicated by relation (2), it is necessary to investigate the effect of the term (ACp) rather than that of Cp alone. This argument is based of course on the fact that the two rotors are not geometrically similar when they have different values of (H/R). As can be seen from Fig.(8), the increase in (H/R) at a value of (NC/R) equal to 0.18 produces an increase in (ACp) over most of the λ_0 range. It is shown [5] that such trend persists for values of (NC/R) 0.09 and 0.27.

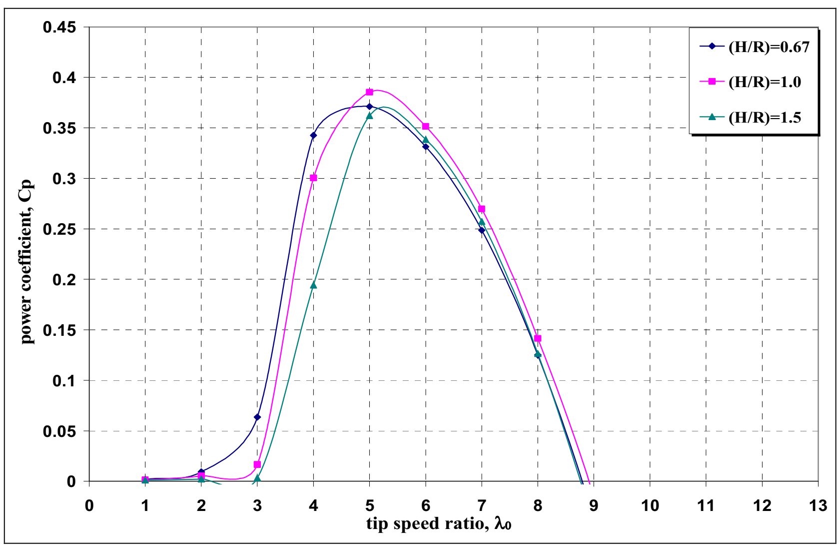

Figure 7: Height to Diameter Ratio Effect on $Cp(\lambda_0)$ Curve for (NC/R) = 0.18.

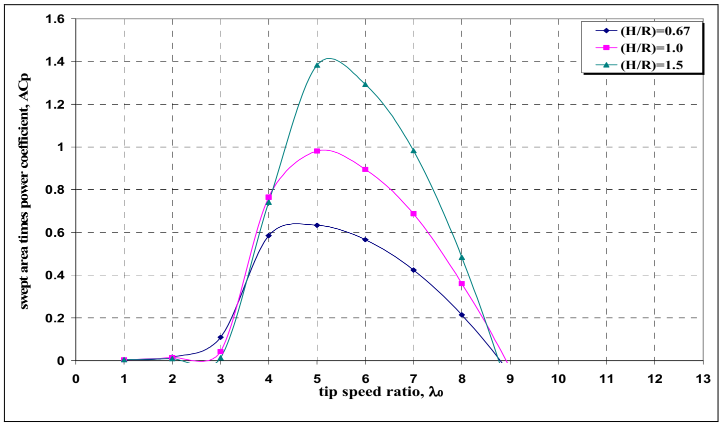

Figure 8: Variation of (ACp) with Tip Speed Ratio for Different (H/R) Values but Constant (NC/R) of 0.18

Influence of Blade Chord Reynolds Number, Re

Figure (9) presents Cp(λ_0) curves for three identical rotor configurations having (H/R)=1.0 and (NC/R)=0.09. The only difference between them is the value of Reynolds number to which the aerodynamic lift and drag force coefficients C_l and C_d data sets correspond. As can be seen from this figure, an increase in Re leads to an increase in Cp over the whole λ_0-range. However, the incremental change in Cp at any given λ_0 decreases as Re increases. Obviously the increase in Re helps in the delay of blade-section stall, or else the increase of stall angle. Such a delay results in an increase in the ratio (C_l/C_d) for any given angle of attack lower than stall angle thus leading eventually to an increase in Cp. The relative increase of Cp with the increase of Re is substantially higher over the low λ_0-range. It is shown [5] that similar behavior concerning the effect of Re on Cp(λ_0) curve exists for higher values of (NC/R).

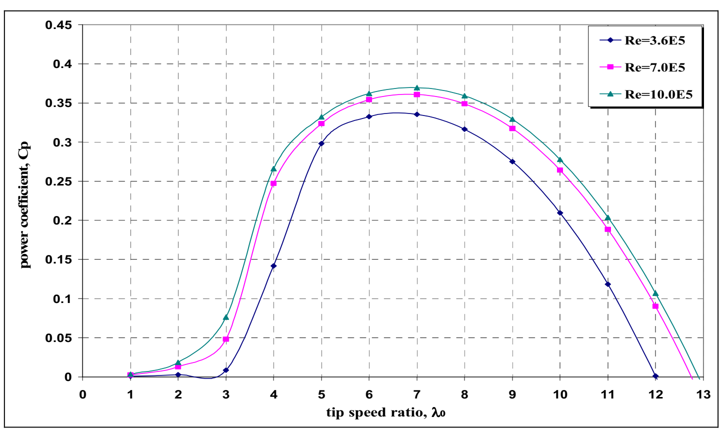

Figure 9: Reynolds Number Effect on Cp(λ_0) Curve for (H/R) of 1.0 and (NC/R) = 0.09

CONCLUSIONS

Based in the results obtained in this study the following conclusions can be drawn:

- Comparison with wind tunnel test results shows that the mathematical model employed in this study predicts overall rotor performance fairly well.
- Within the accuracy of blade-element momentum method utilized, results indicate that for a constant height to diameter ratio, it is the value of (NC/R) rather than the values of N or (C/R) alone which actually determines the shape of $Cp(\lambda_0)$ curve. However, it is expected in practice that for a constant value of (NC/R) the changes in the relative magnitudes of N or (C/R) would have relatively different effects.
- Bearing in mind conclusion (2), results of this study show that an increase in (NC/R) at a given (H/R) leads to:

I. Cp_m increases initially then it decreases, while the value of λ_0 corresponding to Cp_m decreases continuously. Thus decreasing solidity results in a lighter and faster moving rotor.

II. $Cp(\lambda_0)$ becomes more and more "peaky" resulting in a decrease in the extractable power in a given wind speed pattern.

III. Increasing rotor height to diameter ratio at a given value of (NC/R) leads to a substantial increase in the power produced by the rotor.

IV. An increase in rotor blade Reynolds number leads to an increase in Cp over almost the entire $\tilde{\lambda}_0$-range. However, the incremental change in Cp at a given $\tilde{\lambda}_0$ decreases with increasing Reynolds number.

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