Effects of Application of Small-sized Tip fins on Characteristics of Savonius Vertical Wind Turbines

Shahrooz M, Abbaszadeh M, Hosseini S, and Shamloo A.

Abstract**—**The importance of Savonius vertical wind turbines is due to their high performance at low wind speeds and their independence from incoming wind direction. However, low output power has undermined the status of theese turbines. Present study suggests a novel idea; that is the application of tip fins which have the ability to control shear flow in Savonius wind turbines, to enhance the overall performance of savonius turbines. The investigation was carried out through utilization of numerical means. The use of the K-ε: Standard model was validated by modeling experimental tests from one of references and comparing outcomes with experimental data. Results of this study demonstrate that performance of Savonius rotors can be enhanced by over 40 percent with using tip fins. To provide a comprehensive insight toward effects of application of tip devices on savonious turbines, performance of a standard turbine with semicircular blade profile was investigated through different angular positions along with a modified profile. The deep investigation revealed new interesting features such as degradation of turbine performance due to existence of overlap in presence of tip devices.

Keywords**—**Savonoius, Vertical Wind Turbine, Tip Device, CFD.

I. Introduction

Compared to Horizontal Axis Wind Turbines (HAWTs) in the same working regime, Vertical Axis Wind Turbines (VAWTs) produce less power. But their unique capabilities such as the ability to produce power from low speed winds and their independency from wind direction, make VAWTs not only important means to domesticate wind energy, but also a realistic hope to expand natural opportunities to use wind energy. On the contrary, their low operation speed (of wind velocity order) restricts high amounts generation of electricity [1]. Hence, several attempts have been done to maximize performance of Savonius wind mills and therefore achieve higher power outputs.

At first stage of investigations, a maximum power coefficient of 0.31 was reported by Savonius [2]. Consequent studies proposed by Fujisawa and Gotoh [3] and Kamoji et al. [4] resulted in obtaining maximum coefficient of power of 0.173 and 0.17, respectively. Mentioned experiments were carried out in open jet wind tunnel.

It has been observed that geometrical parameters affect the performance of Savonius rotors. Alexander and Holownia [5] conducted an experiment to determine the impact of blade aspect ratio and blade overlap and gap on the performance of Savonius rotor. They claimed that higher aspect ratio results in a value of efficiency of 0.25 in optimum blade arrangement.

Further researches led into modification of Savonius rotors' shape, in order to enhance their power coefficient. Investigating modified Savonius rotors in closed jet wind tunnel, a coefficient of power value around 0.32 was gained [6].

Testing modified Savonius rotor with shaft, Modi and Fernando [6] presented an optimum geometrical parameters. Mentioned parameters were used by Kamoji et al. [7]. They attempted to improve the coefficient of power by changing the geometrical aspects. Besides, the performance of the modified Savonius rotor with shaft, modified Savonius rotor without shaft and conventional Savonius rotor were compared. The maximum power coefficient of 0.21 was attained for modified Savonius without shaft. Moreover, it was pointed out that rotor angles from a rotor angle of 135° to 165° and from 315° to 345° led into negative coefficient of static torque

Due to purity of Savonius vertical wind mill concepts, efforts of optimization of this type of rotors usually cause remarkable enhancment on their performance. As instance Mohemmed et al [8] achieved nearly 40 enhancement in power coefficient by modification of blade shape of obstacle shielded rotors through a complicated optimization process based on using genetic algorithms and Kamoji et al [7] gained nearly 20 percent improvement in rotor power coefficient by modification of a conventional savonius rotor cross section.

However there had been remarkable achievements regarding to enhancment of performance of savonius rotors, current study suggest a novel idea to improve output power of savonius turbines. Application of simple devices on tip of rotor blade intend to control shear flow in savonius rotors and enhance turbine performance.

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II. MODELS

Main cause of power production in a Savonius rotor is the difference of drag coefficient between advancing and returning blade. Each blade's drag force associating with blade radius produces a certain amount of torque in opposite directions but since drag coefficient of advancing blade is much more than returning blade, the resultant torque is the variance between torque of two blades. Fig. 1 demonstrates a conventional configuration of a Savonius rotor.

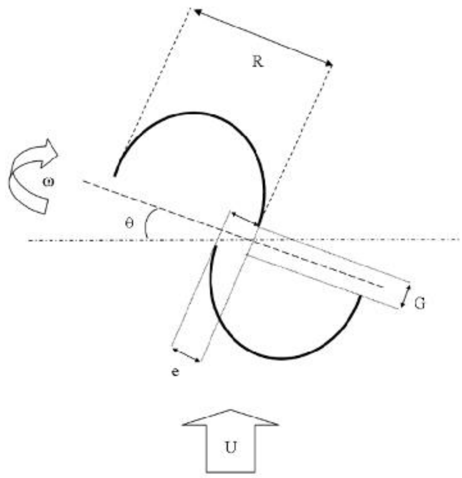

Figure 1- Typical Savonius rotor configuration

The Amount of torque produced by a Savonius rotor is related to the velocity coefficient. Using the notations of Fig. 1, it is defined as [9]:

$$\lambda = \frac{\omega}{U} \qquad (1)$$

This equation expresses the ratio between the tangential velocity of the bucket tip and the velocity of incoming wind. Wilson handbook expresses that the best range of λ for a Savonius rotor is between 0.5 to 1.5 while the best range for a HAWT is between 4 and 7. This fact indicates that a Savonius wind turbine could operate better in a low wind environment than a HAWT.

Non-dimensional coefficients used to describe the performance of a Savonius rotor are torque coefficient and power coefficient, generally expressed as the functions of λ, which are respectively defined as [9]:.

$$C_P = \frac{P}{\rho \quad U^3} \qquad (2)$$

And

$$C_M = \frac{M}{\rho R^2 H U^2} \qquad (3)$$

Where, P is the mechanical power, M torque, ρ air density, and H the height of the rotor. Power coefficient expresses the amount of wind power that the turbine can take up.

To investigate the effects of tip fin application on Savonius rotors, two models were examined. The first model was a conventional Savonius rotor with semicircular blades with 1m radius. The second model was a conventional rotor with a semicircular tip fin having a radius equal to 10 percent of the main blade radius (10 Cm). The main purpose of application of tip fins was to control shear flow which exits from blade tip. Fig. 2 demonstrates concepts and dimensions of the models.

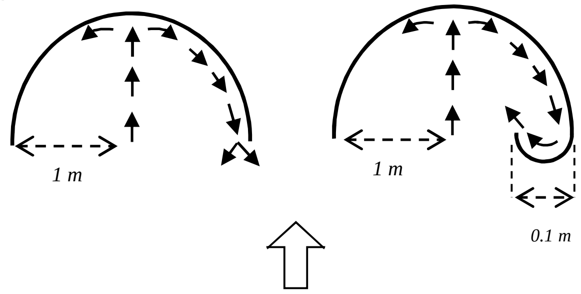

Figure 2- Left: Conventional Savonius rotor, Right: Savonius rotor with tip fin

To evaluate effects of blade geometry on performance of the fin tip one of models had the conventional semicircular cross section but the other rotor had an unconventional cross section consisting of a circular arc on its tip and a tangent line from root to the circular arc. Both models had radius of 1 meter operating in velocity coefficient of 1. Figure 3 demonstrates the second models' (i.e. light model) geometrical specifications.

One step beyond overall performance, this study aimed to provide insight to a vast range of circumstances that a tip fin can be applied on a savonius rotor's blade. On the other hand in order to prevent diversion in resut and thus confusion, based on previous experiences of the team along with a conventional savonius rotor with semi-circle blade profile, a set of optimized profiles was selected to apply the tip fins. This cautiously selected range of profiles represent a vast variation range of geometrical parameters that effect performance of a savonius rotor.

In a previous experience by a same group [12, 13] of researchers, in order to optimize a blade profile of a savonius VAWT, Instead of optimization of a set of random points, in an aggressive innovative attempt a new method was introduced to define the blade profile. In this method the blade consists of a Circular arc in the tip and a tangent line from the tip arc to the root [figure.4].

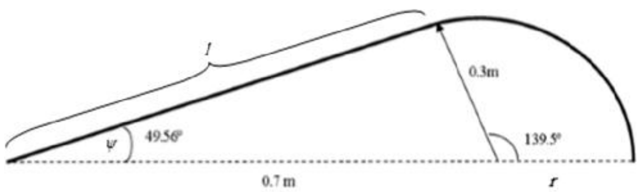

Figure 4 – Optimized Profile Configuration

As it mentioned before, after striking the rotor, the portion of flow stream which captured by advancing blade would move across the blades' span and will exit from blades' tip and root. The exiting stream from the advancing blades' root enters to the returning blade through the overlap between blades and causes a significant enhancement in rotors torque.

The enhancement in torque is due to pressing the returning blade toward rotating direction by the flow stream crossing between blades. From a basic fluid mechanics stand point the force implicated by crossing flow to returning blade is associated with momentum of the crossing flow which itself is a function of mass flow rate and crossing angle of crossing flow. The crossing flows' mass rate is obviously a function of velocity coefficient while its crossing angle is a function of blade geometry.

The Angle of the blade's root with the rotors chord line, which affects the crossing flow's angle, identified as "trailing angle" in current study. From simple geometrical calculations trailing angle can be calculated from:

$$\psi = A \quad \cos\frac{l}{R-r} \qquad (12)$$

And for *l*:

$$l = \sqrt{(R-2r)R} \qquad (13)$$

The parameters are being shown in figure 4. from equation 12 and 13, it is obvious that the in this specific geometry trailing angle (ψ) is a function of tip circles' radius. By this definition the profile could be optimized only by optimization of the tip arc radius

III. Numerical Method

Considering previous experiences in several researches [8, 10] K-ε: Standard model was chosen to evaluate the models through a commercial software package. By studying previous investigations K-ε: Standard turbulence model to achieve data from models through ANSYS fluent Commercial software package. Fluent is a CFD software using the finite sizes method and having the capacity of solving the flow and heat transfer problems in or around complex geometries. In the present Standard k–ϵ turbulence model has been utilized with logarithmic surface function.

The equations of mass and momentum protection used by the program can be written for the compressible and incompressible steady flows as follows in the Cartesian tensor rotation:

$$\frac{\partial}{\partial x_j}\left(\rho.u_j\right) = 0 \qquad (4)$$

Momentum equation:

$$\frac{\partial}{\partial x_j}\left(\rho.u_j.u_i - \tau_{ij}\right) = \frac{\partial p}{\partial x_j} + S_i \qquad (5)$$

In these two equations we have:

- x_i Cartesian coordinate (j=1, 2, 3)
- u_i Absolute velocity components in the direction of x_i .
- p Piezometric pressure = $p_s - \rho_0.g.x_m$ here, p_s is static pressure, ρ_0 is the reference dencity, g is the gravity acceleration andx_m is the coordinate defined by ρ_0
- τ_{ij} Stress tensor components

Here, the stress tensor is as follows:

$$\tau_{ij} = \mu.s_{ij} - \frac{2}{3}\mu.\frac{\partial u_k}{\partial x_k}.\delta_{ij} \qquad (6)$$

Here, μ is the viscosity of the fluid, δ_{ij} (Kronecker delta) and s_{ij} is the change of shape modification tensor and written as follows:

$$s_{ij} = \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \qquad (7)$$

If the Kronecker delta δ_{ij} is

$$i \neq j \Rightarrow 0, i = j \Rightarrow 1$$

Effective viscosity is:

$$\mu_e = \mu + \mu_t \qquad (8)$$

Here, turbulent viscosity is obtained from

$$\mu_t = \rho.f_\mu.C_\mu.\frac{k^2}{\varepsilon} \qquad (9)$$

Turbulent kinetic energy (k):

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}\left(\rho u_j k - \frac{\mu_e}{\sigma_k}.\frac{\partial k}{\partial x_j}\right) = \mu_t s_{ij}\frac{\partial u_i}{\partial x_j} - \frac{2}{3}\left(\mu_t\frac{\partial u_i}{\partial x_i} + \rho k\right)\frac{\partial u_i}{\partial x_i} - \rho\varepsilon \qquad (10)$$

Dissipation rate of turbulent kinetic energy (ϵ):

$$\frac{\partial}{\partial}(\rho \quad) + \frac{\partial}{\partial x_j}\left(\rho.u_j.\varepsilon - \frac{\mu_e}{\sigma_\varepsilon}.\frac{\partial}{\partial x_j}\right) = C_1 f_1\frac{\varepsilon}{k}\left[\mu_t s_i \frac{\partial u_i}{\partial x_j} - \frac{2}{3}\left(\mu_t\frac{\partial u_i}{\partial x_i} + \rho \quad\right)\frac{\partial u_i}{\partial x_j}\delta_i \quad\right] - C_2 f_2 \rho\frac{\varepsilon^2}{k} - C_3\rho \quad \frac{\partial u_i}{\partial x_i} \qquad (11)$$

In the above equations, the subscripts i,j,k and the empirical constants for the turbulence model $C_\mu, \sigma_k, \sigma_\varepsilon, C_{1\varepsilon}, C_{2\varepsilon}$ are equal to 1, 2, 3 and 0.09, 1.0, 1.3, 1.44, 1.92, respectively.

However, utilization of the numerical method was precisely based on later successful efforts [8, 10]. But in order to validate the use of numerical means, a model from reference [11] was examined and results were compared with experimental data from the reference. As Fig. 3 demonstrates, numerical and experimental results were fairly close to each other.

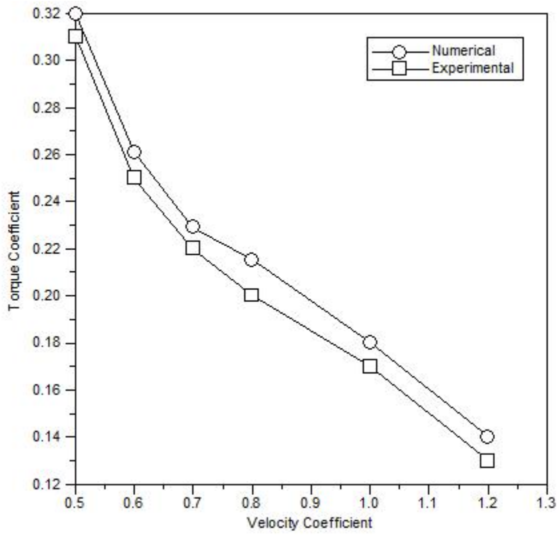

Figure 3- Comparison of numerical and experimental results

Multipliers can be especially confusing. Write "Magnetization (kA/m)" or "Magnetization (10^3 A/m)." Do not write "Magnetization (A/m) × 1000" because the reader would not know whether the top axis label in Fig. 1 meant 16000 A/m or 0.016 A/m. Figure labels should be legible, approximately 8 to 12 point type.

IV. Results

In order to provide a comprehensive insight on the effects of tip device application on Savonius rotors, outcome data were analyzed by considering two major concerns. First to study the effects on overall performance and then to study overall behavior and optimum design parameters of the rotor under implication of tip device.

The performance of conventional and modified rotors' was plotted against different velocity coefficients [Fig. 4]. Results indicate nearly 40 percent advantage for the sample with tip devices at the optimum velocity coefficient. However, variance of the profiles is not constant in different velocity coefficients.

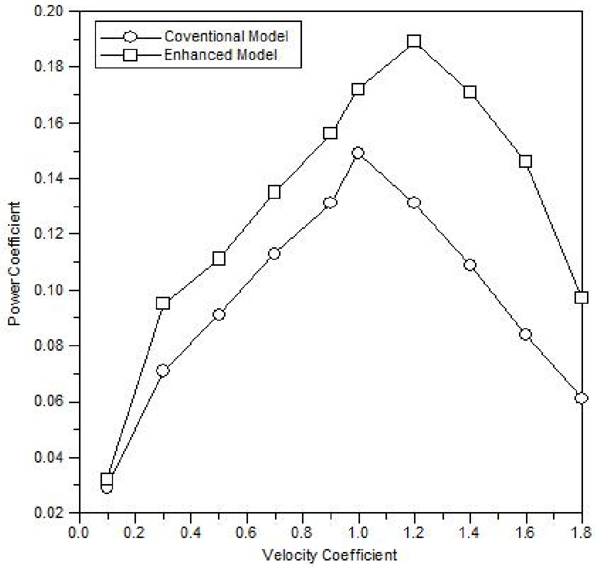

Figure 4 – Comparison of conventional and enhanced model

Fig. 1 also indicates that by application of the tip device, optimum velocity coefficient would be increased which eventually results in increment of Betz limit of the rotor. Additionally, considering enhancement values achieved by Mohammad et al. [8] (more than 30 percent) and Komaji et al [7], it can be concluded that tip devices provide more enhancement in Savonius wind mills performance, offering a simpler and undemanding solution.

Comparison of M-θ profiles [Fig. 5] of the models on their optimum velocity coefficient demonstrate that variation trend is almost the same, but variance between maximum and minimum torque is higher in the modified model.

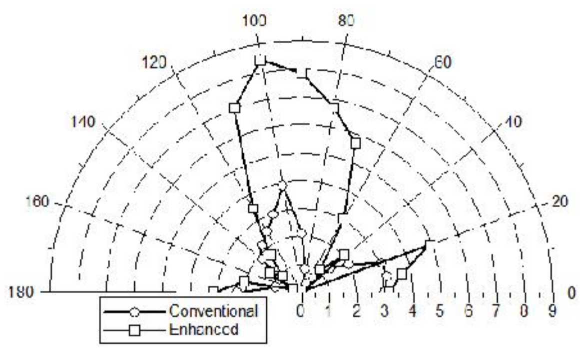

Figure 5- Variation of produced torque in different angular positions

Distribution of power coefficient in different overlap ratios for the modified rotor [Fig. 6] demonstrates that despite previous experiences on conventional models [11], in the modified model, by increasing the overlap the power coefficient would be decreased. This observation suggests that tip fins have better capability of controlling shear stream in the plate.

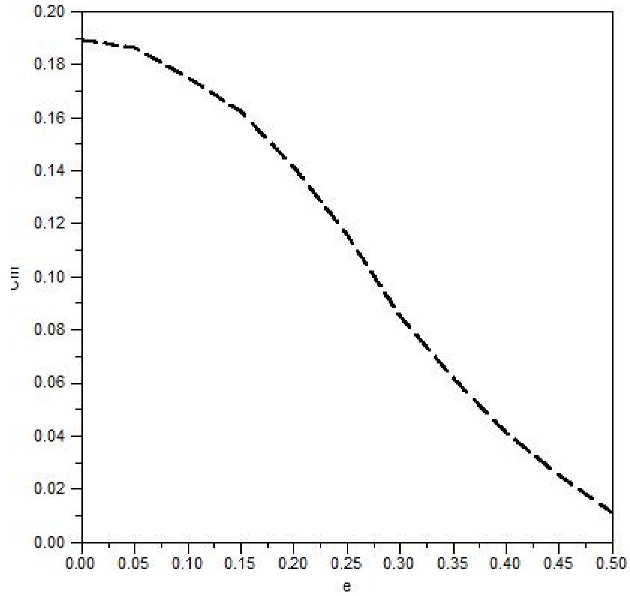

Figure 6- Effects of increment of overlap ratio on power coefficient

In case of application of tip devices on the rotor with optimized profile results were somehow close to the semicircular profile but with enhancement in power and torque coefficients. Same as figure 5, Figure.9 shows effects of application of tip devices on rotors with optimized profiles. From a previous experience following effects of changing tip circle radius and trailing angle was discovered in performance of different rotors [12]:

Table.1-Specifications of models

Model	$\bar{r}$	ψ
S.1	0.1	12.7
S.2	0.2	27.8
S.3	0.3	49.56
S.4	0.4	76.2
S.5	0.5	90

Table.2- optimum overlap and its Cm for each model

Model	S.1	S.2	S.3	S.4	S.5
Optimum e	0.315	0.286	0.273	0.256	0.244

As for the optimized sample with tip radius ratio of 0.3, effects of application of tip device effects of application of a tip fin on output power coefficient was plotted against advance ratio [fig.7]:

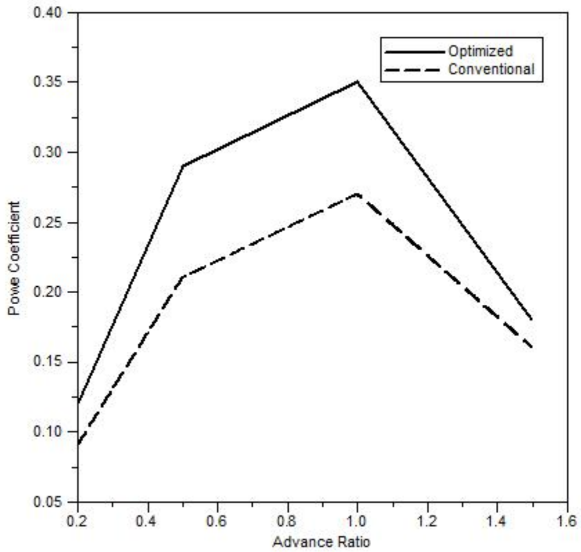

Figure 7. Effects of application of the tip device on the optimized rotor

A negligible decrease in optimum advance ratio is observable from figure 8 but overall this shows that performance of savonius vertical axis wind turbines remains the same upon application of tip fins. As for behavior of the turbine figure 6 show similar occurrences as figures 4 bringing the conclusion that application of tip fins in other blade profiles would not cause any significant abnormality in rotor's behavior however in reaching a final design and in order to compare vibration (and thus fatigue and noise) characteristics of the turbine, changes in natural frequency of the turbine as result of changes in the geometry should be considered.

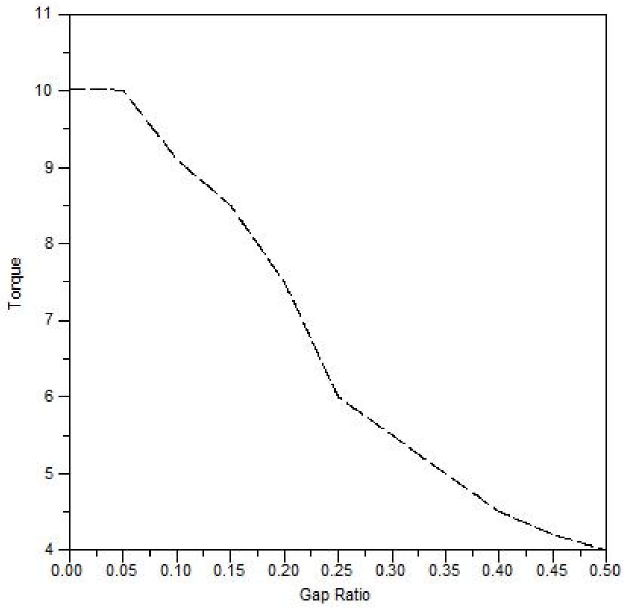

Fig.8 Effects of increment of overlap ration on output torque

Also an important parameter in application of tip devices was effects of tip fin angle on overall performance of the rotor. Fig.9 demonstrates effect of tip device angle on overall torque coefficient of the rotor.

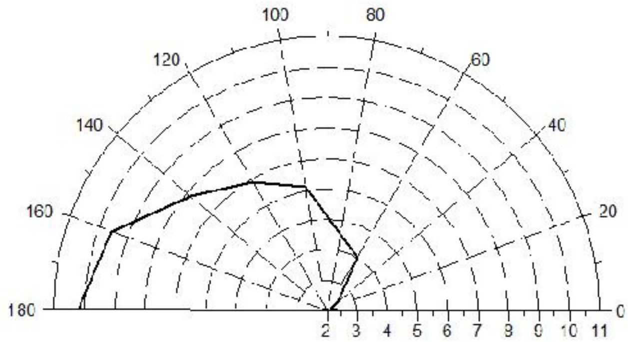

Figure 9- Effect of angle of tip device on performance of the rotor

There is a considerable shift between 40 and 80 degrees in accordance to a general shift in momentum of the outgoing flow suggesting that in any attempt to apply a tip fin on these turbines, an optimization procedure should be considered. Although Savonius wind turbines are known as drag based turbines (which implicates that main cause of rotation in these kind of turbines is the shear stress. Studying pressure contours as being showed in fig.10 implicates that distribution of dynamic pressure plays an important role at least in the performance of implicated tip device.

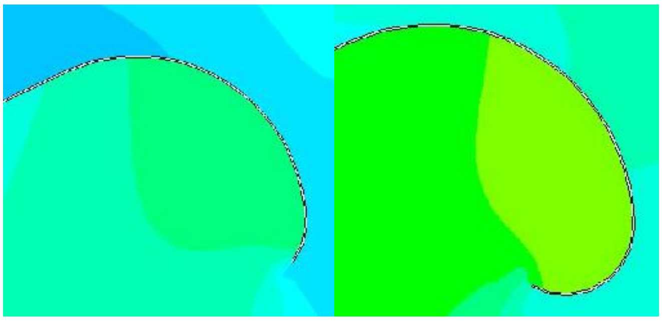

Figure 10. Pressure distribution along the optimized profile with 20 degree and 110 degree fins

V. Conclusion

Results of this study, based on a trusted and validated numerical method, presented application of tip fins on savonius vertical wind turbines as low cost solution which can effectively sideline known disadvantage of low output power of these turbines in further applications. Results also demonstrated that however significant changes in geometrical parameters of the rotor could cause changes in effects of application of tip fins on savonius rotors, these changes are predictable and does not contribute to any curtail characteristic of the rotor such as vibration or flow separation.

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