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ANALYSIS AND COMPUTATIONAL SIMULATIONS OF THE FLOW THROUGH STATORS DESIGNED FOR POWER AUGMENTATION IN SAVONIUS WIND TURBINES

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Abstract. *Computational Fluid Dynamic were employed to perform simulations of viscous flows through stators designed for power augmentation of Savonius wind turbines. Numerical analysis were carried out for flow fields around stators with and without circular section, all fitted with concentrator and diffuser. The mass flows through the stators were calculated, the obtained values with conclusions from the 1-D momentum theory make it possible to predict which type of stator schould contribute more to increase the power coefficient. It was showed that the stator shaped like a cylinder promotes flow deflection to the region in which the advancing blade would act. The low pressure created after the cylindrical stator, due to boundary layer separation, also increase mass flow and reduce the dimension needed in the diffuser. The type of flow that occurs through the cylindrical stator promotes an increase of mass flow in the region where the flow would provide positive torque to the turbine, which would increase the power coefficient in the turbine operation, without the need of using a large diffuser. All simulations were based on the Finite Volume Method and implemented using the commercial software Star-CD, that solve the continuity and Reynolds Averaged Navier Stokes Equations to obtain the results. The results provided by the software were considered valid only when their values have less than 0.01% of difference in relation to provided values by the software in previous calculations iteration. The simulations were performed considering the flow with its velocity equal to the undisturbed flow velocity that would occur in the operation of the turbine Savonius, with a Reynolds number based on turbine diameter, equal to* 3.32×10^5*. In the simulations, the turbulence model* $k-\omega$ *SST, in its Low-Reynolds approach, it was used. The dimensionless normal distance from the walls was kept less than 3. For all simulations, the turbulence boundary conditions are turbulence intensity of 0.01 and length scale of 0.005 m. The differencing scheme Linear Upwind Differencing (LUD) and the hybrid wall function were also used. To resolve the pressure-velocity coupling the algorithm SIMPLE was used. In calculation domain, it was used an unstructured tetrahedral mesh with refinement near the stator.*

Keywords*: Savonius wind turbine, stators, CFD, mass flow, power augmentation*

1. INTRODUCTION

Common impediments to the exploitation of wind resources are low energy density of the wind in various locations around the world and the high cost of devices used in the conversion of wind energy into useful energy forms. An option to turn wind energy more attractive is the use of power augmenters accompanied by cheaper power generation technologies. The more common power augmenters are static shrouds, or stators. Thus, a wind turbine with this type of device consists of a rotor, rotating part, and a stator, static part. According to South *et al.* (1983), the stators more able to increase the power coefficient of the wind turbines are made primarily by a concentrator, to increase the flow velocity toward the rotor, followed by a diffuser, to reduce the velocity again, increasing the pressure to the atmospheric level. Therefore, more mass of fluid per unit time is directed through the rotor due to the flow concentration caused by the concentrator and by the diffuser. As more mass flow is directed through the rotor, more useful energy is obtained in the same projected area of the rotor, resulting in an increase of the power coefficient of the wind turbine.

Cheaper technologies for wind power generation, as the Savonius rotor, can be used with stators to improve the attractiveness in the exploitation of the wind resources. This type of wind rotor, whose first model was developed and patented by Sigurd J. Savonius in 1929, according Vance (1973), has been intensively tested and investigated for eight decades. From research, emerged various settings and accessories for this type of rotor. Using the knowledge developed it is possible to build Savonius rotors with power coefficient close to 0.3, as can be found in Saha *et al.* (2008). The use of a Savonius rotor with a stator of cylindrical shape, as described by Sabzevari (1978), can provide power coefficient greater than 0.5.

This paper presents computational simulations for the incompressible flow of a hypothetical viscous fluid through stators designed to Savonius turbines. The numerical analysis results from the solution of continuity and Reynolds Averaged Navier Stokes Equations using the Finite Volume Method, implemented using the commercial software Star-CD. The stators considered in simulations are of non-cylindrical and cylindrical formats. The purpose of these simulations was calculated velocity and pressure distributions and the mass flow through the stators. With the values of mass flows and conclusions obtained from the analysis based on 1-D momentum theory, applied to wind energy, the stators could be evaluated qualitatively. Conclusions of present work, as well as the methodology adopted here, are an important tool to define the physical model design, which will be built in the next phase of present research.

2. THE 1-D MOMENTUM THEORIES AND POWER AUGMENTATION DUE TO STATORS

Analysis based on equating of the 1-D Momentum for ideal wind turbines help to understand how the stators can increase the efficiency of a wind turbine.

Considering the axial wind turbines operation, as Hansen (2008) and Horlock (1978), a turbine can be represented as a permeable disc, by the Actuator-Disc Theory. This is shown in Fig. 1. The disc allows the fluid passage through it, but decreases the flow velocity from V_o to u and, thereafter, to u_1. It works as a drag device. The extracted flow energy is equivalent to useful energy that the turbine supplies. On disc, there is not also conversion from kinetic energy to heat and there is only flow in one direction. The pressure of the flow remains equal to p_o away from the rotor, but close to it there is a change in pressure that is equal to Δp. The force, or thrust, that the disc perform to slow down the flow, T, depends on Δp and the projected area of the rotor, A, according to Eq. (1).

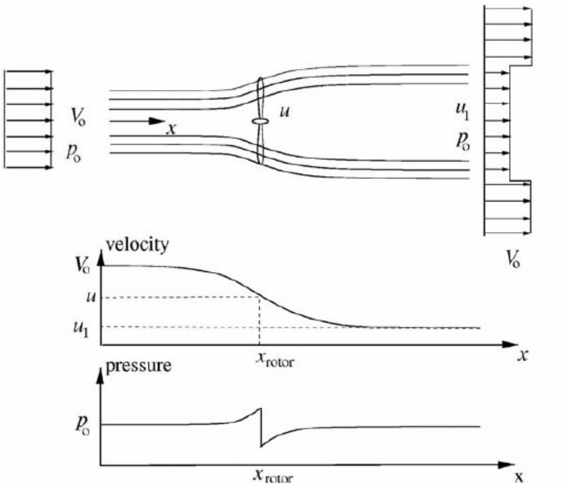

Figure 1. Ideal Flow Through The Actuator Disc (Source: Hansen, 2008)

$$T = \Delta p\, A \tag{1}$$

As is described in Hansen (2008), using the equations of the continuity, Bernoulli, momentum and energy conservation, with the Eq. (1), the power coefficient of an ideal wind turbine, C_P, and the axial thrust coefficient, C_T, as functions of a induction factor, a, may be deducted. The relations of u, C_T and C_P with a are shown by Eq. (2), (3) and (4) respectively. By the Equation (4) is easy verify that the maximum value of C_P is $^{16}/_{27}$ that occurs when a is equal to $^{1}/_{3}$. This C_P value is known in literature as the Betz limit.

$$u = (1-a)V_o \tag{2}$$

$$C_T = 4\, a\,(1-a) \tag{3}$$

$$C_P = C_T\,(1-a) \tag{4}$$

The Betz limit is valid only for operation of turbines without stators. It is possible to exceed the Betz limit as showed in Hansen (2008). If a rotor is placed inside of a stator with cross-section shaped like airfoils (Fig. 2) this limit can be exceeded. The flow through the stator generates a lift force, which creates a ring vortex, which induce high mean velocity that increase the mass flow through the rotor, as described by Vries (1979). If the stator walls are more similar to airfoils, greater will be the mass flow through the rotor, for this design concept.

In another concept of wind turbine that is designed to overcome the Betz limit, studied by South *et al.* (1983), the stator consists of a concentrator upstream of the rotor and a diffuser downstream. The concentrator reduces the area of flow passage, increasing the flow velocity. The diffuser increases the area of flow passage, reducing the flow velocity and increasing pressure, inducing the fluid mass that already passed through the plan of the rotor to outside the stator.

The effects of the concentrator and the diffuser combined induce the mass of fluid that would pass through a larger area cross a smaller area, increasing the mass flow through the rotor.

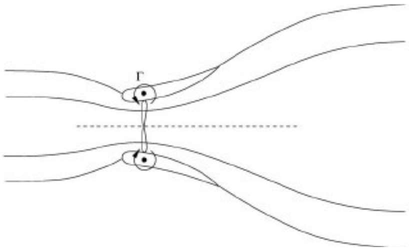

Figure 2. Ideal Flow Through a Wind Turbine with Stator (Hansen, 2008)

The relationship of axial velocity at the rotor plan, denoted by V_2, with the velocity of undisturbed flow, V_o, provides the increase in velocity occurred due to the stator, ε, (Hansen, 2008) according to Eq. (5). A rotor 1-D analysis in a stator provides the Eq. (6), for the power coefficient of a turbine with stator, C_{Pe}, in which P is the rotor power and ρ is the fluid specific mass.

$$\varepsilon = \frac{V_2}{V_o} \tag{5}$$

$$C_{Pe} = \frac{P}{\frac{1}{2}\rho\, V_o^3 A} = \frac{T\, V_2}{\frac{1}{2}\rho V_o^2 \frac{V_o}{V_2} V_2 A} = C_T\, \varepsilon \tag{6}$$

Combining Eq. (6) with (4) gives the Eq. (7).

$$\frac{C_{Pe}}{C_P} = \frac{\varepsilon}{(1-a)} \tag{7}$$

The Eq. (8) and (9) are valid for the mass flows through rotors without stators, $\dot{m}$, and with stators, $\dot{m}_e$.

$$\frac{\dot{m}}{\rho V_o A} = \frac{\rho (1-a) V_o A}{\rho V_o A} = (1-a) \tag{8}$$

$$\frac{\dot{m}_e}{\rho V_o A} = \frac{\rho V_2 A}{\rho V_o A} = \varepsilon \tag{9}$$

With Equations (7), (8) and (9), the Eq. (10) can be easily obtained. This equation shows that an increase in mass flow through a rotor due to stator produces an increase in the power coefficient of a wind turbine directly proportional to the increase in mass flow.

$$\frac{C_{Pe}}{C_P} = \frac{\dot{m}_e}{\dot{m}} \tag{10}$$

The same reasoning can be applied to the ideal flow through a radial wind turbine. According to Newman (1983), the existence of two induction factor may be considered: a_1, related to the advancing blade action, and a_2, related to the returning blade operation. This is shown in Fig. 3. The torque, Q, of the turbine can be expressed by Eq. (11), where R is the radius of the wind turbine and T_1 and T_2 are the forces that reduce the flow velocity. If the term $T_1 - T_2$ in the Eq. (11) is increased, while V_o remains constant, the power coefficient of the wind turbine also will be increased.

Thus, with the use of stators, the flow can be deflected to the region in which the advancing blade operates. Therefore, more mass of fluid per time unit focuses on the advancing blade while in the region in which the returning blade serves a decrease occurs in the mass flow. This increases the power coefficient of the wind turbine because the power increases and V_o is maintained with the same value.

$$Q = T\,R = \left(T_1 - T_2\right)R \tag{11}$$

According to Newman (1983), a radial wind turbine also can be imagined as a double actuator-disc, provided there is torque when the blades are upstream and downstream of the axis, simultaneously. By the Double Actuator-Disc Theory, there is the extraction of kinetic energy in two plans and each plan features an induction factor across its area, as shown in Fig. 4. Making up these considerations, can be deduced that the turbine power is the sum of the power acquired by each plan. The power coefficient of the rotor, then, can be expressed by Eq. (12), in which e_1 and e_2 are induction factors of the first and second plans respectively. If $e_1 = {}^1/_5$ and $e_2 = {}^3/_5$, C_P will reach its maximum value, equal to ${}^{16}/_{25}$, which exceeds in 8% the Betz limit. However, if the rotor is mounted inside of a stator, and this theory was considered, C_P could have a value greater than this, because the mass that flows through the area $A - A_1$ also cross through the second plan. With this, more power would be obtained in the second plan. Furthermore, a stator can also contribute to an increase in the mass flow in the first plan.

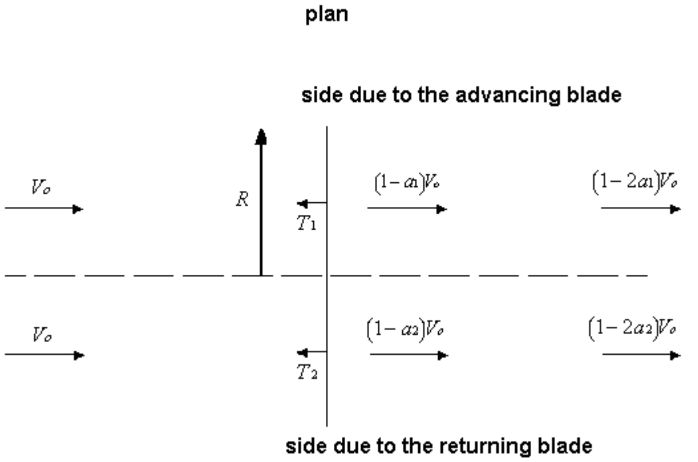

Figure 3. Single Actuator-Disc for Radial Wind Turbine. Adapted from Newman (1983)

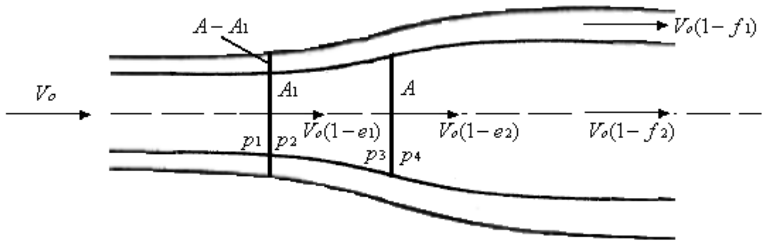

Figure 4. Double Actuator-Disc for Radial Wind Turbine. Adapted from Newman (1983)

$$C_P = \frac{\left(p_1 - p_2\right)A\,V_o\left(1 - e_1\right) + \left(p_3 - p_4\right)A\,V_o\left(1 - e_2\right)}{\frac{1}{2}\,\rho\,A\,V_o^{\,3}} \tag{12}$$

Theoretically, drag radial wind turbines can not achieve large power coefficients and tip speed ratio greater than one (Gasch and Twele, 2002). For example, the value for the maximum power coefficient is equal to 0.16, for a Persian windmill and equal to 0.08 for a cup anemometer. Therefore, Savonius turbines, which operate from the pressure drag, may not necessarily be added to this group of turbines. Such devices do not work from pure drag, there are lift forces working also on their blades, according to Kamoji *et al.* (2009). Therefore, the theories for the wind turbines operation based on 1-D momentum can be used to explain the gain in efficiency due to the stators in Savonius turbines.

3. CYLINDRICAL STATORS IN SAVONIUS WIND TURBINES

The analysis based on 1-D momentum applied to the operation of ideal wind turbines suggests that stators can provide an increase in the power coefficient of the turbines. However, stators with inadequate geometry can not contribute to significant gains in power.

According to South *et al.* (1983), the actual stators produce considerable loss of kinetic energy of the flow. It is easy to convert static pressure into dynamic pressure, or velocity up the flow, as is done in a concentrator, but is much more difficult to reverse this process. The output diameter of the diffuser should be similar to the diameter occupied by the expanded flow downstream of the actuator-disc, so the diameter of the outlet diffuser must be greater than the diameter of the input concentrator. The length of the diffuser should be long enough so that the adverse pressure gradient is not very intense. In short diffusers or with very large output diameters in relation to the diameter of the entry, usually the boundary layer separation occurs as can be seen in Fig. 5.

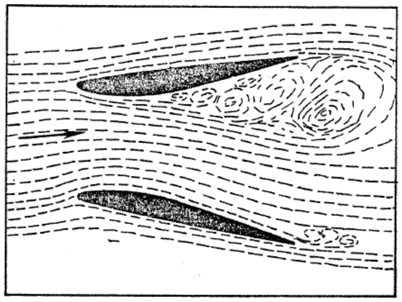

Figure 5. Flow Separation Downstream of a Diffuser (Source: South *et al.*, 1983)

Typical dimensions of good performance concentrator and diffuser can be seen in Figure 6. The dimensions of that device are not appropriated to wind turbine applications, in view of inadequate quantity of material, weight and aerodynamic losses. According to South *et al.* (1983), various techniques, such as the use of slots to prevent the boundary layer separation and dynamics inducers using tip vanes to diffuse flow, have been developed over time to reduce the size of the diffuser without loosing the flow diffusion quality.

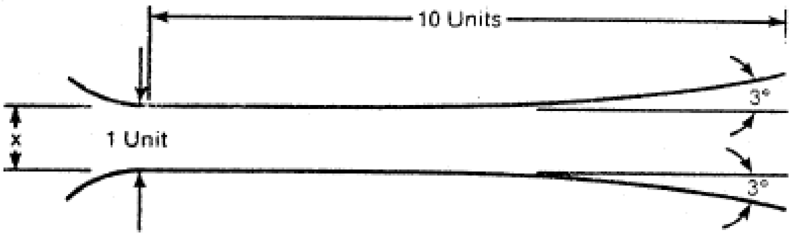

Figure 6. Typical Proportions for an Efficient Passive Diffuser (Source: South *et al.*, 1983)

Stators with cylindrical shapes similar to the studied by Sabzevari (1978), with the diffuser outlet having dimensions similar to the concentrator inlet, can help to reduce the diffuser size. Sabzevari, in his study, compared the performance of a cylindrical stator Savonius turbine with the performance achieved by a non-cylindrical stator Savonius turbine (see Fig. 7-a). He concluded that the two turbines had an income higher than the performance of the Savonius turbine without stator and that the turbine with cylindrical stator showed the best performance among all. According Sabzevari, the boundary layer separation on the outer surface of the cylindrical stator creates a region with low pressure downstream of the diffuser, as shown in Fig. 7-b. This region with low pressure improves the mass diffusion behind the stator. This increases the mass flow through the rotor, producing higher power coefficients and tip speed ratios, λ .

4. COMPUTATIONAL SIMULATIONS

The results of Sabzevari (1978) in performance tests for cylindrical stators inspired the computational simulations based on Finite Volume Method and performed with the commercial software Star-CD, for the two-dimensional flow, in steady state, of a hypothetical viscous fluid through stators designed to Savonius turbines. The simulations were performed for a non-cylindrical stator and another with cylindrical shape. These stators are shown in Fig. 8. The dimensions indicated in the study of Sabzevari were chosen to use. Among these dimensions are included the inlets of concentrators and the outlets of diffusers both with the same dimensions of the Savonius rotor diameters, D_r, which could be housed inside the stator. Other parameters indicated by Sabzevari are the aperture angle, θ , equal to 33° and the concentrators and the diffusers targeted in the way shown in Fig. 8. Thus, according Sabzevari, a Savonius rotor can get good performance if operate inside these stators. However, a yawing motion device is required if a turbine this type operate under wind conditions found in the field.

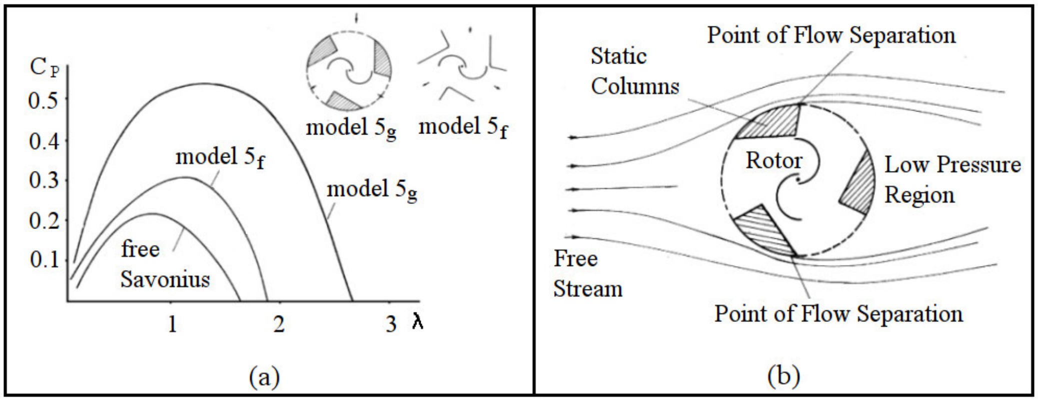

Figure 7. Power Augmentation in a Savonius Turbine due to a Cylindrical Stator. Adapted from Sabzevari (1978)

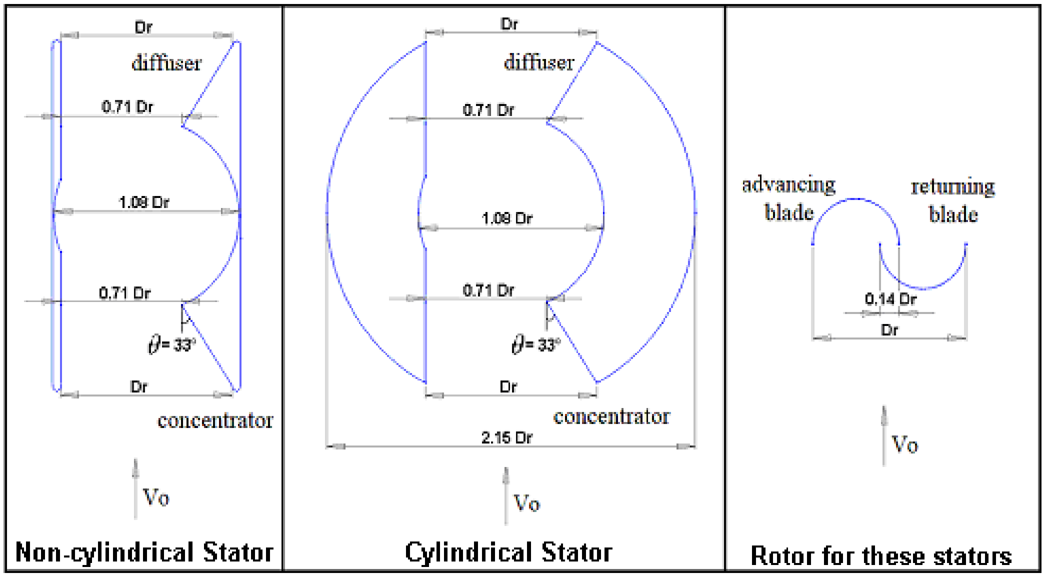

Figure 8. Stators Covered in this Study

The velocity and pressure distributions in the flow were obtained as results of the simulations. These results enabled that the analysis of flow and calculation of the mass flow through the stators could be performed. For the results to be obtained, the equations of mass conservation and the momentum equation were solved by the software Star-CD. The software uses the discretization method by the finite volumes for solving such equations. The results provided by the software were considered valid only when their values have less than 0.01% of difference in relation to provided values by the software in previous calculations iteration.

The calculation domain and mesh used to perform the simulations are shown in Fig. 9. The dimensions of the domain were chosen so that the ends were moved away disturbance imposed by the obstacle (stator), as recommended by Petry (1993) and Malalasekera and Versteeg (1995). In this domain, it was used an unstructured tetrahedral mesh with refinement near the stator.

The simulations were performed considering that the velocity at the domain entrance is equivalent to the undisturbed flow velocity, V_o. This velocity was considered equal to that which would occur upstream of a Savonius rotor with a diameter equal to D_r in a flow of Reynolds number, calculated basing on D_r, equal to 3.32 x 10^5. At the end of the domain, the pressure was considered as known. The no slip condition was applied on the stators surfaces and above another contours of the domain the free slip condition was assumed.

In the simulations, the turbulence model $k-\omega$ SST, in its Low-Reynolds approach, it was used because it gives good results for stream lines have large curvatures. The dimensionless normal distance from the walls (y^+) was kept less than 3. For all simulations, the turbulence boundary conditions are turbulence intensity of 0.01 and length scale of 0.005 m. The differencing scheme Linear Upwind Differencing (LUD) and the hybrid wall function were also used. To resolve the pressure-velocity coupling the algorithm SIMPLE was used (StarCD, 2008).

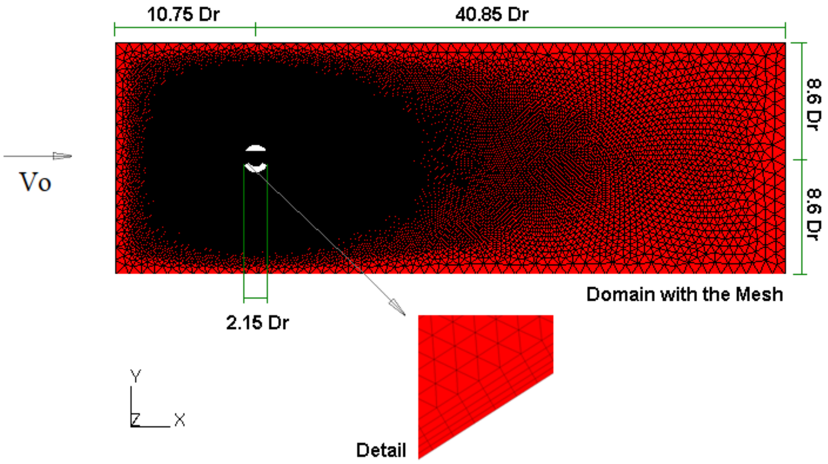

Figure 9. Calculation Domain and Mesh

5. RESULTS AND DISCUSSION

In the Figures 10 and 11, the obtained results of the simulations in two stator types to the vectors of the velocity components in directions x and y, V_x and V_y, are displayed. It can be seen that higher velocities occur in flow through the stator of cylindrical shape. In both flows the stream is deflected to the region in which the advancing blade of a Savonius rotor, with dimensions shown in Fig. 8, would act. This, would contribute to an increase in the power coefficient of the rotor.

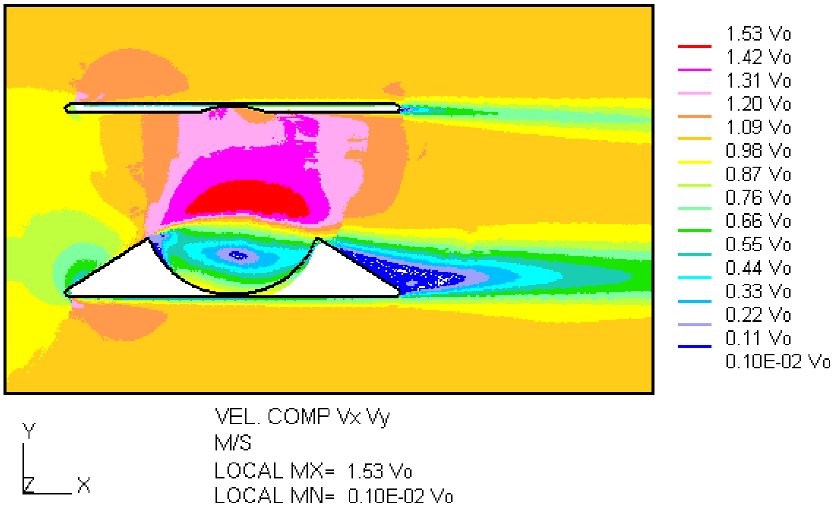

Figure 10. Velocity Components V_x and V_y in the Flow Through the Non-Cylindrical Stator

In Figure 12, the values for the velocity component V_x in the flow through the non-cylindrical stator along the center line of the stator are shown. The curve of Figure 12 was integrated so that the mass flow could be obtained. The same was done for the curve given in the Fig. 13, about the values for the velocity component V_x in the flow through the cylindrical stator, through its center line. In both cases, the same mass that flows by the concentrator inlet also flows through the diffuser outlet. That, in accordance with the Double Actuator-Disc Theory, would can to contribute to an increase in the power coefficient of Savonius rotors that would operate within these stators. It can be seen, in these figures, which there are areas with negative velocities in the regions in which returning blades would act, due to a recirculation existing there. With this, the returning blades that would act in those regions would have yours negative torques reduced and the power coefficients of the Savonius rotors could be increased.

The obtained value for the mass flow through the non-cylindrical stator equals to 0.82 x $\dot{m}_{rotor}$ and the obtained value for the flow through the cylindrical stator equals to 0.84 x $\dot{m}_{rotor}$. In this study, it was considered that $\dot{m}_{rotor}$ is equivalent to the mass flow which flows in a stream without disturbances and with velocity equal to V_o through an area equal to projected area of a Savonius rotor with similar dimensions to appeared in Fig. 8. Although the mass flows in both stators be smaller than $\dot{m}_{rotor}$, the power coefficient of a Savonius rotor that would operate in such stators would be increased because the same amount of mass that enters by the concentrators leaves by diffusers. The flow deflection to the region in which the advancing blade of the turbine would operate in the two stators also would help increase the power coefficient of the rotor. In the flow through the non-cylindrical stator, the mass flow in the area in which an advancing blade would act equal to 1.37 x $^{1}/_{2}\,\dot{m}_{rotor}$ and mass flow in the area in which a returning blade would act equal to 0.26 x $^{1}/_{2}\,\dot{m}_{rotor}$. For the flow through the cylindrical stator, the obtained values for the mass flow in these areas are equal to 1.43 x $^{1}/_{2}\,\dot{m}_{rotor}$ and 0.28 x $^{1}/_{2}\,\dot{m}_{rotor}$ respectively.

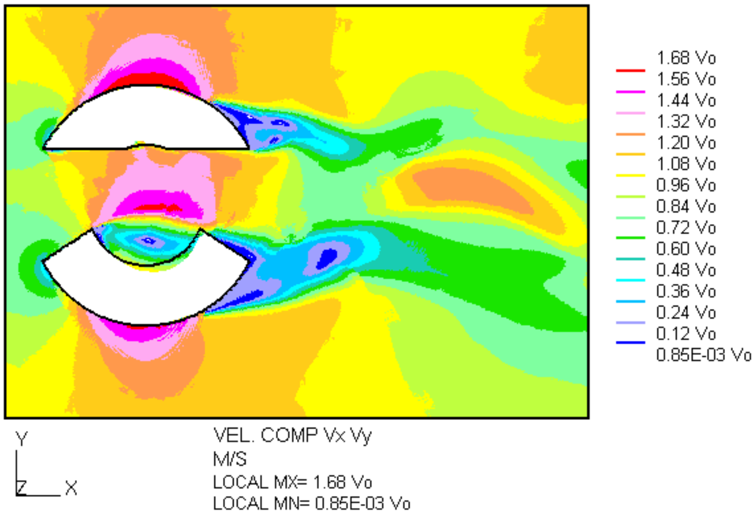

Figure 11. Velocity Components V_x and V_y in the Flow Through the Cylindrical Stator

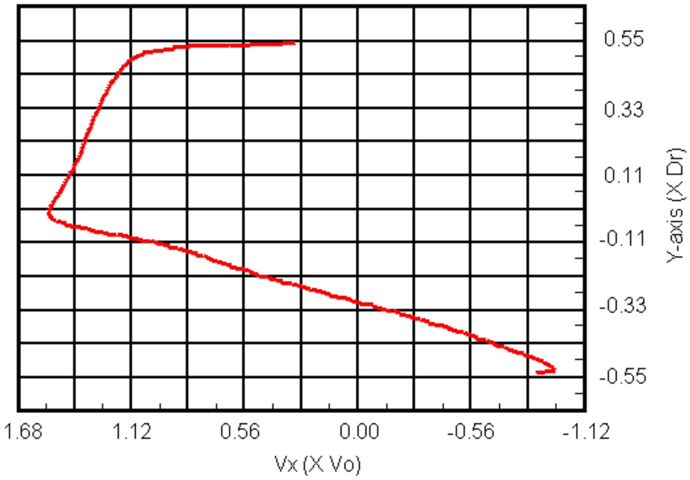

Figure 12. Velocity Component V_x in the Flow Through the Non-Cylindrical Stator in the Stator Center Line

In the simulations, it was verified that the mass flow through the cylindrical stator is greater than the mass flow through the stator non-cylindrical. This can be better understood when the obtained results for the pressure distribution in the two simulations are analyzed. These results are shown in Fig. 14 and 15. The figures show a pressure gradient rather adverse to the passage of fluid in the non-cylindrical stator diffuser. This gradient causes a major blockage to the fluid passage in addition to cause the appearance of a large recirculation in the diffuser. The pressure gradient in the diffuser of the cylindrical stator is not as adverse to the passage of fluid as that which exists in the non-cylindrical stator diffuser. This is due to boundary layer separation that occurs on the external surfaces of the cylindrical stator. The boundary layer separation reduces the pressure downstream of the diffuser, doing the pressure gradient there better to diffuse the fluid molecules to outside of the stator. These obtained results for the pressure distribution are in accordance with the explanation of Sabzevari (1978).

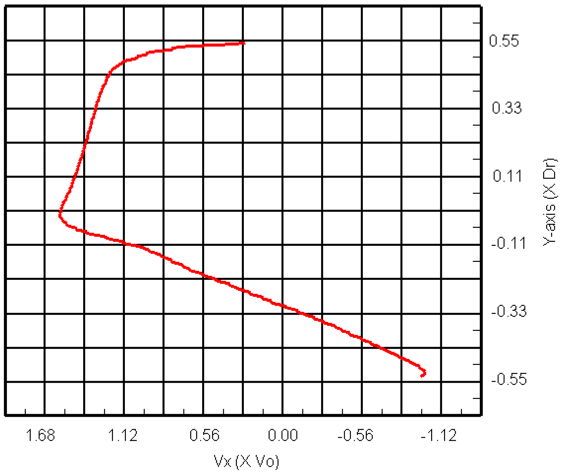

Figure 13. Velocity Component V_x in the Flow Through the Cylindrical Stator in the Stator Center Line

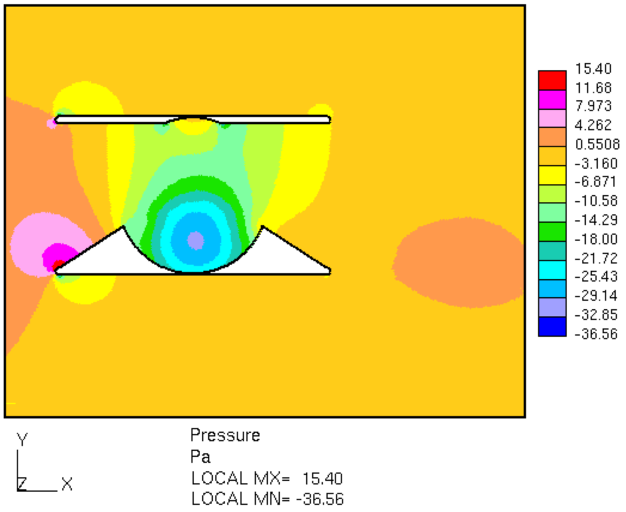

Figure 14. Pressure Distribution in the Flow Through the Non-Cylindrical Stator

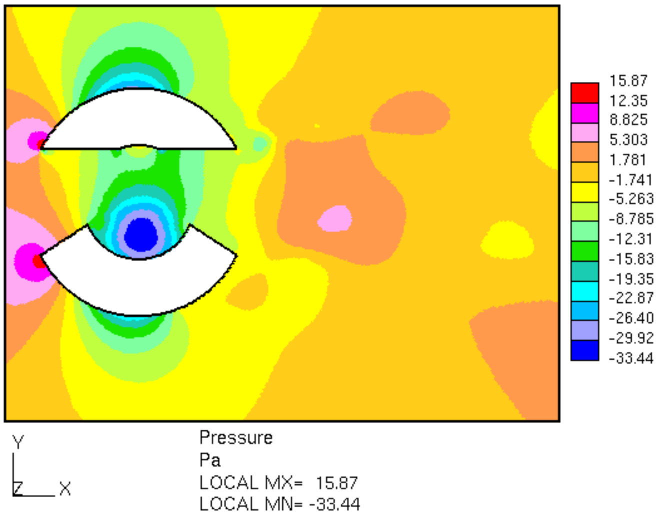

Figure 15. Pressure Distribution in the Flow Through the Cylindrical Stator

6. CONCLUSIONS

The use of stators together with cheap technologies such as Savonius rotors to produce wind turbines can do the use of wind resources more attractive. The results obtained in the simulations performed in this study together with interpretations of theories based on 1-D momentum for the wind turbines operation help to show that a stator shaped like a cylinder, designed for Savonius turbines, can promote an increase in the exploitation of wind energy without using high technology.

A stator with a cylindrical geometry similar to that was studied in this work is compact, with little constituent material. The mass flow through it is equal in all its internal sections. It promotes concentration of flow to the region in which the advancing blade of a Savonius wind turbine would act. The boundary layer separation that occurs on their external surfaces creates a pressure gradient downstream of the diffuser that is, when compared with the gradient found in the diffuser of a stator with non-cylindrical geometries similar to those studied in this work, more favorable to the diffusion downstream of the stator. All these characteristics do a Savonius rotor, operating within a stator of this type, to can to manifest a power coefficient greater than the power coefficient of a free Savonius rotor.

Results presented here, as well as the methodology adopted, are an important tool to define the physical model design, which will be built in the next phase of present research. The physical model will be tested in a wind tunnel. Comparing experimental data with numerical results we intend to improve present methodology, and apply it to the analysis of optimal parameters for shrouded Savonius wind turbine.

7. ACKNOWLEDGMENTS

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