

# Flow Physics of a Three-Bucket Savonius Rotor using Computational Fluid Dynamics (CFD)

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## Abstract

Vertical axis wind turbine (VAWT) type Savonius rotor is self-starting, inexpensive, less technicality & high productivity wind machine, which can accept wind from any direction without orientation, and provides high starting torque. That is why Savonius rotor is widely used for water pumping, heating, aerating & other household applications. The main limitation of Savonius rotor is its low power coefficient. Thus, there is a need for research to improve its performance. In this paper, an attempt was made to study the flow physics of a three-bucket Savonius rotor using Fluent 6.0 CFD software. The height of the rotor was 20 cm & bucket length was 8 cm. Four overlap conditions in the range of 12.37% to 25.87% were considered. The flow physics of the rotor with overlap variation was analysed with the help of velocity and pressure contours of the rotor. And it was observed from the analysis that the overlap of 19.87% was the optimum overlap condition at which pressure and velocity differences across the rotor were the highest for which maximum power extraction by the rotor would be possible at that overlap condition.

## Keywords

Savonius rotor, power coefficient, overlap, tip-speed ratio, CFD, flow physics

## I. Introduction

Owing to acute energy crisis that most developing countries are facing today, the interest in renewable energy sources has increased many folds in the recent past. Renewable energy sources like wind energy can help in reducing dependency on fossil fuels. Wind power is environment friendly that results in no air-pollution, greenhouse gas emission, water pollution etc. Wind is a domestic energy source, abundantly available in the earth crust. Expanding wind power development brings job to rural communities, and increases tax revenue. It has been estimated that roughly 10 million MW of energy are continuously available in the earth's wind. Wind energy can be utilized to windmills, wind farms & wind turbines, which in turn drive a generator to produce electricity. According to the data released by Global Wind Energy Council (GWEC), wind energy developing countries have raised the net wind energy installed capacity to a record high of 194,390 MW [1] (GWEC, 2010). The top ten wind power market in terms of MW installed with market share and the growth of installed wind energy capacity from 1996-2010 are shown in fig.1(a) & (b) respectively. In India, the interest in windmills had grown in the late fifties and early sixties. Now, India has the world's largest programme for renewable energy with wind energy potential alone is of about 45000 MW.

To maximize the convertibility of wind energy, the major focus is on proper designs of wind rotors and its generators. In places where wind speed is relatively low and varies appreciably with seasons, there is major need to do research on wind rotors, which can run in low wind velocity and can be used in a small scale manner in remote and rural areas where electricity is scarce. Savonius rotor of vertical axis type could be suitable for these conditions. S.J. Savonius initially developed the vertical axis Savonius rotor in late twenties [2]. The concept of Savonius rotor is based on the

principle developed by Flettner, which is formed by cutting a cylinder into two halves along the central plane and then moving to two semi-cylindrical surfaces sideways along the cutting plane, so, that the cross-section resembled the letter 'S' (fig.2). To determine the best geometry Savonius tested more than 30 different models of S-rotors in the wind tunnel and reported very encouraging results. The best of the rotor models had an power coefficient of 31%. Between Sixties and nineties, many researchers [3-14] had worked on different designs of Savonius rotor and evaluated their power coefficients. Sharma et al [15] conducted model tests on two-bucket S-rotor, and obtained maximum power coefficient of 52%. Biswas et al. [16] conducted model tests on three-bucket S-rotor, taking tunnel blockage into consideration, and reported maximum power coefficient of 38%. Applications of CFD for the aerodynamic analysis of Savonius rotor and other types of vertical axis wind turbines are found in the available literature. Menet J. & Bourabaa N [17] did a parametric investigation on the power coefficient of two-bucket Savonius rotor and concluded that the power coefficient can be improved by judiciously selecting its important geometric parameters like height, diameter, overlap ratio, end plate dimensions etc. Katsuya I. & Toshio S [18] simulated numerically the flow over a two-bucket Savonius rotor by solving 2D finite volume equations using an upwind scheme for unstructured mesh. Their results showed good matching with the experimental values of power coefficient, aerodynamic coefficients. Brad C. Cochran et al. [19] numerically simulated the flow patterns in and around a two-bucket Savonius rotor of thirteen different configurations to optimize the blade configuration by using Reynolds-stress 5-equation turbulence model. They further concluded that 2D CFD simulation was sufficient as the blades rotate in the same plane as the approaching wind, thereby reducing the computational time and effort. Debnath et al. [20] evaluated the performance of a three-bucket Savonius rotor in combination with three-bladed Darrieus rotor with overlap variations using Fluent 6.0 CFD software. The result showed good matching of computational and experimental power coefficient for all overlap conditions. In the present paper, the performance of a three-bucket Savonius rotor was analyzed computationally by using Fluent 6.0 CFD software.

## II. Physical Model

The buckets of the rotor were 8 cm in chord, 3 mm in thickness, and 20 cm in height. Rotor was fixed to the shaft using nut & bolt arrangement. Ball bearing was used to support the central shaft of the rotors at the base. Washers & nuts having knurled surfaces were used to change the overlap. Overlap is the distance of the inner edge of the bucket from the axis of rotation assuming the arc is carried to the full semi-circle. Different overlap conditions like 12.375%, 19.875%, 21.375%, 25.875% etc were obtained by changing the overall diameter of the rotor. The central shaft of the rotors was 1.5 cm in diameter and 25 cm in length. The base was 7 cm wide and 2.4 cm thick. Schematic fig. of the Savonius rotor is shown in fig.3.

## III. Computational Modeling

Two-dimensional computational domain has been made for the three-bucket Savonius rotor. Since the vertical axis wind turbine

is inherently a 2-D device, where the blades rotate in the same plane as the approaching wind, a two-dimensional simulation is deemed to be sufficient for this application [21]. The computational domain of the three-bucket Savonius rotor along with the boundary conditions is shown in the fig.4 (a). Velocity inlet and outflow conditions were taken on the left and right boundaries respectively. The top and bottom boundaries of the computational domain, had symmetry conditions on them. The buckets and central shaft were set to standard wall condition. Computationally modeling was done in gambit of the Fluent 6.0 package. On the four surrounding edges of the computational domain, uniform grid spaces were taken. However, non-uniform meshing was done on the buckets. The density of mesh is high near the bucket peripheries & tips, and it decreases away from the rotor. This was done to capture the separated rotor wakes. Each mesh element is considered as a control volume. All dependent variables are calculated at the centroid of the control volumes. Unstructured (triangular) meshing was done on the face external to the rotor as shown in fig.4 (b). The computations were initially carried out with various levels of refinement for the mesh until the Grid Independent Limit (GIL) mesh [22] was attained. The resolution of the mesh at the important areas was varied in an attempt to reach grid independent limit mesh. Each refinement level was solved in Fluent with the same set of input parameters. The various levels of refinement used for the grid independence analysis of the rotor are shown in table 1. The variation of pitching moment coefficient of the bucket with respect to refinement levels is shown in the fig. 5. The refinement level 6 of table 1 was considered for final simulation.

#### IV. CFD Analysis of three-bucket Savonius rotor

The finite difference form of Navier-Stokes equation for incompressible flow of constant viscosity was solved by the in-built functions of the fluent CFD package. Similarly, the finite difference forms of continuity and k-ε turbulence model equations are solved. The equation for conservation of mass, or continuity, can be written in vector form as:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{V}_r) = \dot{S}_m \quad (1)$$

Where, value of  $\dot{S}_m$  is zero for steady-state flow

The vectored momentum equation in terms of relative velocity,  $\vec{V}_r$  can be written as

$$\frac{\partial}{\partial t} (\rho \vec{V}_r) + \nabla \cdot (\rho \vec{V}_r \vec{V}_r) + \rho (\alpha \vec{\omega} \times \vec{r} + \alpha \vec{x} \times \vec{r}) = -\nabla p_s + \rho \vec{g} + \nabla \cdot (\vec{\tau}) \quad (2)$$

According to the eddy viscosity concept of the Stokes' hypothesis for Newtonian fluids, the Reynolds stress tensor,  $\vec{\tau}$  can be expressed as

$$\vec{\tau} = \mu [(\nabla \vec{V}_r + \nabla \vec{V}_r^T) - \frac{2}{3} \nabla \cdot \vec{V}_r I] \quad (3)$$

The simplest and most widely used two-equation turbulence model is the standard k-ε model that solves two separate transport equations to allow the turbulent kinetic energy and its dissipation rate to be independently determined. However realizable k-ε turbulence model is fast and more accurate than the standard k-ε turbulence model in terms of predicting separated flow from the wind rotor. It solves two separate transport equations to allow the turbulent kinetic energy and its dissipation rate to be independently determined. The realizable k-ε model is extensively used for planar and round jet flows, rotating homogeneous shear flows and for flows involving separation and recirculation. The realizable k-ε turbulence model is used for the present flow case that involves separation and also recirculation. The modeled transport equations

for k and ε in the realizable k-ε model are:

$$\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_i} (\rho k u_i) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k - \rho \epsilon - Y_M \quad (4)$$

$$\frac{\partial}{\partial t} (\rho \epsilon) + \frac{\partial}{\partial x_i} (\rho \epsilon u_i) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x_j} \right] + C_{1\epsilon} \frac{\epsilon}{k} (G_k) - C_{2\epsilon} \rho \frac{\epsilon^2}{k} \quad (5)$$

$$\text{Where } C_1 = \max \left[ 0.43, \frac{\eta}{\eta + 5} \right], \quad \eta = S \frac{k}{\epsilon} \quad (6)$$

In this study, steady state incompressible flow was considered. The numerical simulation was carried out by solving the conservation equations for mass and momentum and by using an unstructured-grid finite volume methodology coupled with moving mesh technique [23]. The standard k-ε turbulence model with enhanced wall function was utilized. The method of dynamic grid or rotating reference frame was implemented in which the bucket is fixed in the view of an observer who is moving with the rotating frame of reference. Single rotating reference frame was considered, where the blades along with the support arms and the central shaft rotate relative to the incoming fluid stream. The sequential algorithm, Semi-Implicit Method for Pressure-Linked Equation (SIMPLE), was used for solving all the scalar variables. For the convective terms of the momentum equations and also for the turbulence equations, the second order upwind interpolating scheme [24] was adopted.

#### V. Contour Plot Analysis of Three-Bucket Savonius Rotor

The contour plot analysis gives an idea about the flow physics of a wind rotor and its power production mechanism. In the present study, relative velocity magnitude (velocity of the rotor relative to wind) and static pressure contours of the Savonius rotor are analysed. The contour plots are obtained for tip speed ratio at which power coefficient of the rotor is the highest for each overlap condition. Fig. 6(a) to fig.6(d) show the relative velocity contours of the three-bucket Savonius rotor for overlap conditions of 12.37%, 19.87%, 21.37% & 25.87%. The relative velocity magnitude contours show that there is a decrease of relative velocity magnitude from the upstream side to the downstream side of the rotor. Fig. 6(a) for 12.37% overlap shows that relative velocity decreases from 27.5 m/sec upstream to 17.6 m/sec downstream across the rotor. Fig. 6(b) for 19.87% overlap shows that it decreases from 33.1 m/sec upstream to 19.9 m/sec downstream across the rotor. Therefore, with increase of overlap to 19.87%, relative velocity difference across the rotor increases that in turn increases the power extraction from wind by the rotor. However, for 21.37% overlap, fig.6(c) shows that it changes from 29.3 m/sec to 18.4 m/sec across the rotor. Therefore, the difference of relative velocity across the rotor decreases at this overlap meaning drop in power extraction. For 25.87% overlap, it further decreases as shown in fig.6 (d). Fig. 7(a) to fig.7 (d) show the static pressure contours of the rotor for the aforesaid overlap conditions. These pressure contours show a decrease of static pressure from the upstream side to the downstream side across the rotor, which results in useful lift for the rotor. At 12.37% overlap (fig.7a), static pressure decreases from 113 Pascal to -150 Pascal from upstream side to downstream side of the combined rotor. At 19.87% overlap (fig.7b), static pressure decreases from 568 Pascal to 179 Pascal from upstream side to downstream side. Therefore, with increase in overlap from 12.37% to 19.87%, the static pressure drop across the rotor increases. However, as the overlap increases to 21.37% (fig.7c) and then to 25.87%, the magnitude of static pressure drop

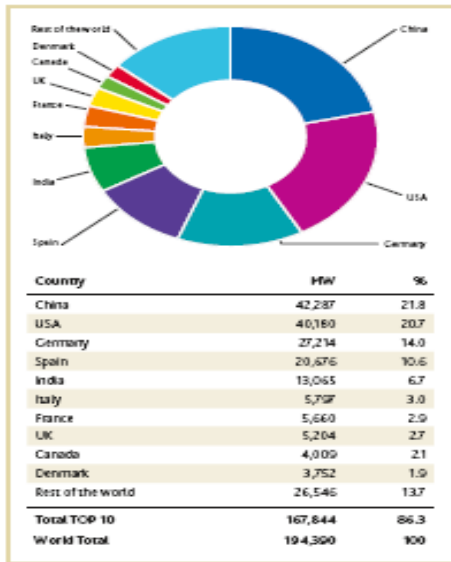
across the rotor decreases. As shown in fig.7d for 25.87% overlap, static pressure decreases from 499 Pascal to 190 Pascal from upstream to downstream side of the rotor; hence compared with 19.87% overlap, change of static pressure across the combined rotor decreases. Therefore, overlap condition of 19.87% is the optimum overlap in terms of pressure and velocity variations for which performance of the Savonius rotor is also the highest at that overlap condition.

## VI. Conclusion

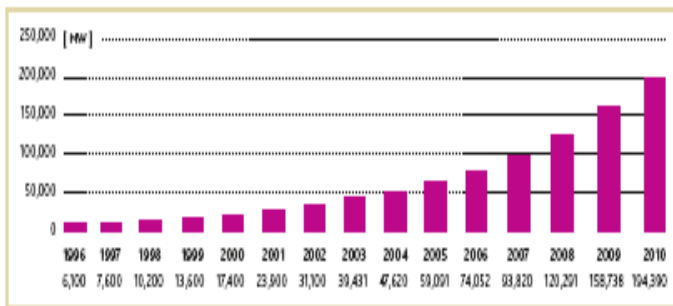
- (i) The contour plots of relative velocity magnitude of the Savonius rotor show that relative velocity decreases from upstream to downstream side of the rotor, the difference of which increases with the increase of overlap from 12.37% to 19.87% but then decreases with further increase of overlap to 25.87%, signifying drop in power extraction from wind by the rotor at overlap higher than 19.87%.
- (ii) The contour plots of static pressure of the Savonius rotor show that static pressure decreases from the upstream to downstream side of the rotor, which results in useful lift for the rotor. With increase of overlap from 12.37% to 19.87%, the static pressure difference across the rotor increases but then decreases with further increase of overlap to 25.87% meaning drop in lift force of the rotor.
- (iii) Out of the four overlap conditions analyzed, overlap of 19.87% is the optimum overlap at which both pressure and velocity differences across the rotor are the highest for which high performance of three-bucket Savonius rotor can be expected at that overlap condition.

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(a)



(b) Source- GWEC 2010

Fig. 1 (a & b) : (a) Top ten wind power markets with market share and (b) Growth of installed wind energy capacity from 1996-2010

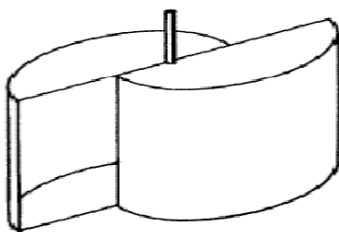


Fig. 2: Savonius Rotor

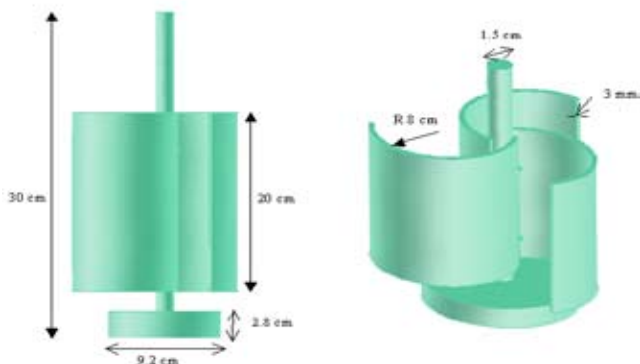


Fig. 3: Physical model of the 3-bucket Savonius Rotor

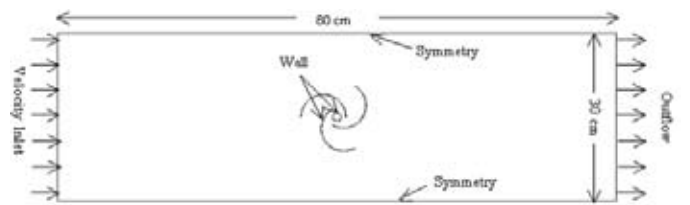


Fig. 4 (a): Computational domain and boundary conditions of the 3-bucket Savonius rotor

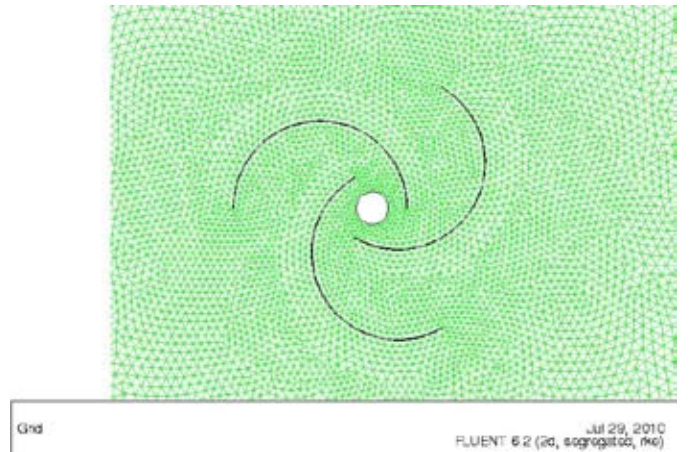


Fig. 4(b): Computational mesh around 3-bucket Savonius rotor (zoomed-in)

Table 1: Details of refinement levels of the grid of the 3-bucket Savonius rotor

Refining Level	No. of Nodes	No. of faces(Triangular)
1	4083	11896
2	9041	26640
3	16345	48422
4	31034	92299
5	43073	128296
6	49798	148411

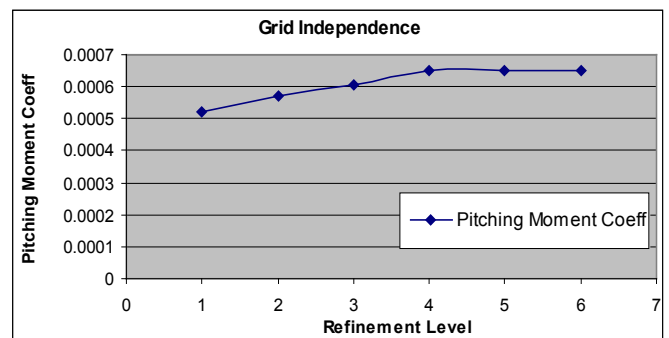


Fig. 5: Variation of pitching moment coefficient with refinement levels of the grid of the 3-bucket Savonius rotor

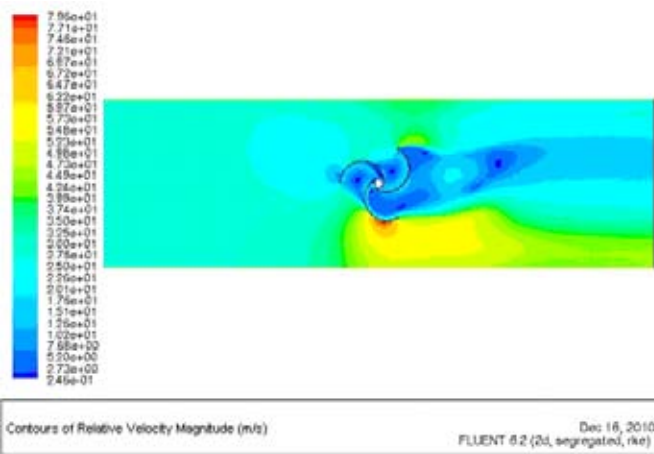


Fig. 6(a): Relative velocity magnitude contour of 3-bucket Savonius rotor for 12.37 % overlap

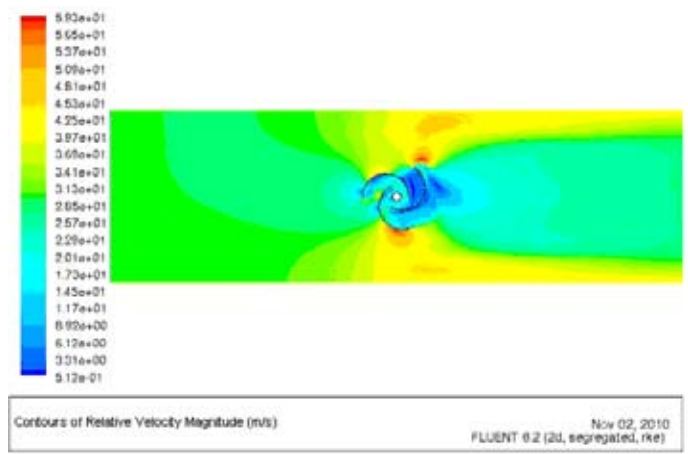


Fig. 6(d): Relative velocity magnitude contour of 3-bucket Savonius rotor for 25.87 % overlap

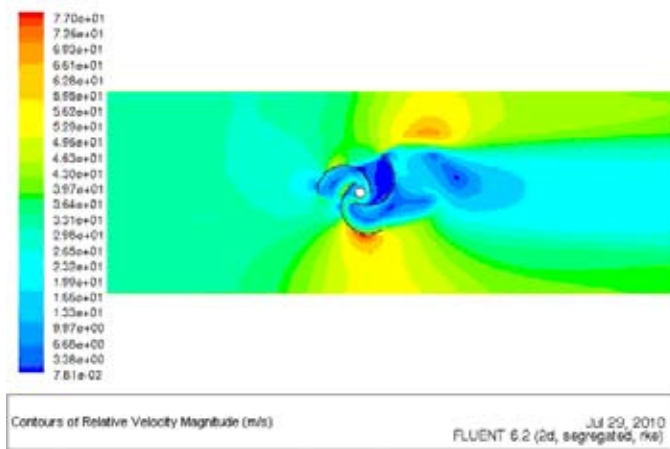


Fig. 6(b) : Relative velocity magnitude contour of 3-bucket Savonius rotor for 19.87 % overlap

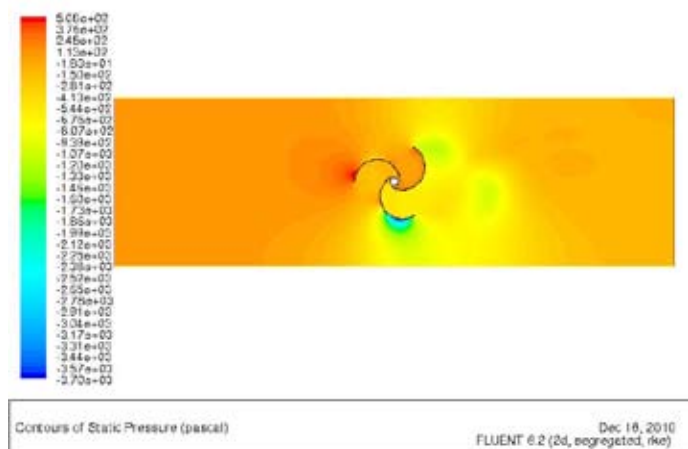


Fig. 7(a): Static pressure contour of 3-bucket Savonius rotor for 12.37% overlap

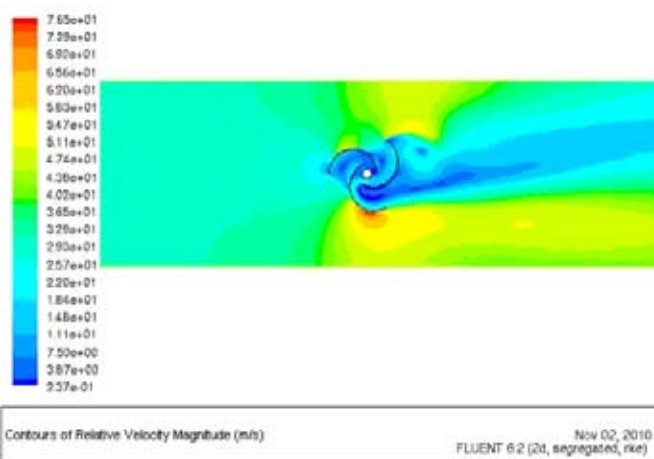


Fig. 6(c): Relative velocity magnitude contour of 3-bucket Savonius rotor for 21.37% overlap

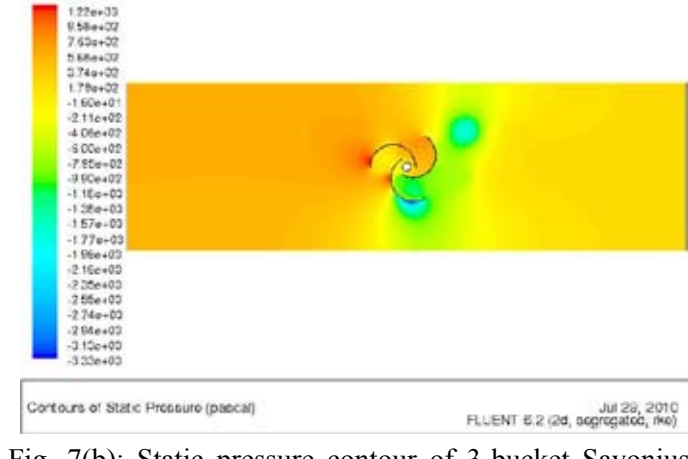


Fig. 7(b): Static pressure contour of 3-bucket Savonius rotor for 19.87 % overlap

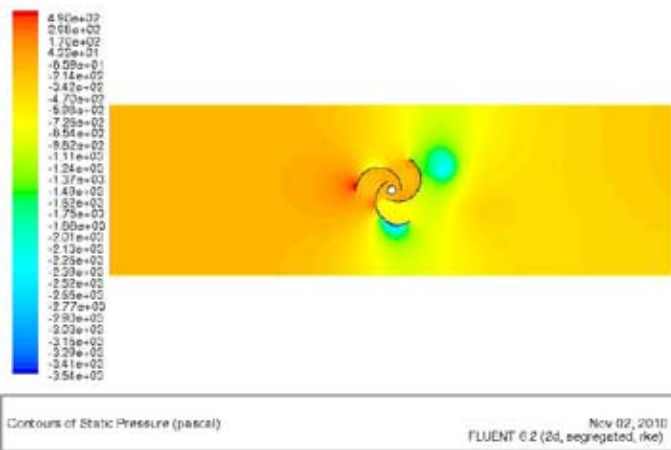


Fig. 7(c): Static pressure contour of 3-bucket Savonius rotor for 21.37 % overlap

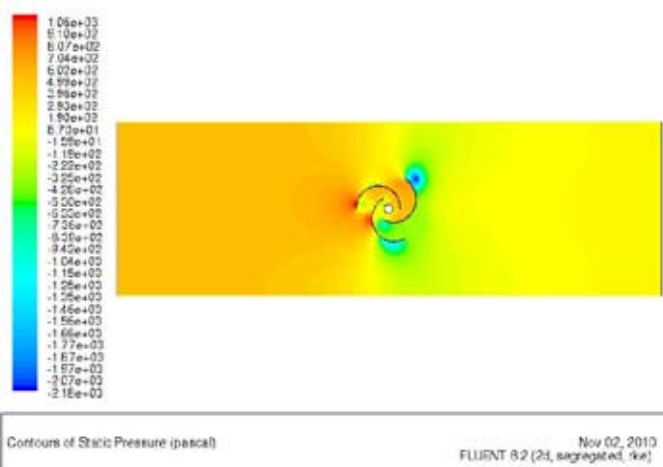


Fig. 7 (d): Static pressure contour of 3-bucket Savonius rotor for 25.87 % overlap



Rajat Gupta, a PhD from Indian Institute of Technology Delhi, has been a Professor in Mechanical Engineering Department at NIT Silchar since 1996. About 114 papers of his have been published in various national/international journals/conferences. He is currently holding the post of Director of NIT Srinagar, Hazratbal, Srinagar (J & K).



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