Numerical investigations of an influence of the aspect ratio on the Savonius rotor performance

Krzysztof Sobczak
Institute of Turbomachinery, Lodz University of Technology, 219/223 Wolczanska, 90-924 Lodz, Poland
krzysztof.sobczak@p.lodz.pl

Abstract. An influence of the aspect ratio on the Savonius rotor performance was investigated. Three-dimensional 3D numerical models of the classical Savonius rotor equipped in two semi-circular buckets with an overlap gap and endplates were studied for different aspect ratios. The simulation results were verified against the experimental data and a blockage effect was taken into account. An increase in the power coefficient and the tip speed ratio for the maximal power coefficient with a growth in the rotor aspect ratio was observed. An effect of the wind displacement beyond the rotor was more intensive for lower aspect ratios.

1. Introduction
The most important advantages of a Savonius rotor are its simple design and low manufacturing costs, high starting torque, wind direction independence, low flow and rotation speeds which contribute to low noise, etc. All these aspects make it suitable for applications in urban areas. However, the rotor is characterized by low efficiency with typical values of the power coefficient in the range \( Cp = 0.15 - 0.20 \) [1], [2]. Its improvement is necessary to treat the Savonius wind turbine as a reasonable alternative to other wind turbines. Therefore, the turbine is subject to wide experimental and numerical investigations devoted to different aspects of the turbine design.

One of the parameters which influence the Savonius rotor efficiency is its aspect ratio, i.e., a ratio of the rotor height to its diameter (AR = H/D). As indicated in [2], there was a limited number of systematic experimental studies concerning an aspect ratio impact on the Savonius rotor performance. In general, losses at tips of the buckets as well as the wind displacement beyond the rotor lower its efficiency. Therefore, rotors with higher aspect ratios have higher efficiency due to relatively lower tip losses and lower wind displacement. The performance of low aspect ratio rotors can be improved by an application of endplates which limit tip losses and have a similar effect as that produced by a higher aspect ratio. Thus, in the majority of the experiments where the aspect ratio impact was investigated, endplates were used.

Apart from research on low aspect ratio rotors, e.g., at AR = 0.6 – 1.0 in [3], where the highest power coefficient was obtained for AR = 0.7, other studies indicate that the highest efficiency is reached for much higher aspects. In [4], [5] the highest efficiency was attained for the highest aspect under study (AR = 2.5 – 5.0), whereas in [6] the maximum was obtained for AR = 6.0, with a much lower value for AR = 7.0. The investigations presented in [7] show high changes in the maximal value of the power coefficient in the range of AR < 2 and no significant changes above this value. Also in [5] much higher changes were observed for AR < 1 than for higher AR. According to other studies, Savonius rotors with aspect ratios of about 1 – 2 yielded sufficiently good performance. However, the majority of existing Savonius turbines were installed with low aspect ratios (AR ≤ 1) due to structural
reasons [1], [2]. The aspect ratio of a Savonius rotor can be adjusted to specific requirements. Rotors with a higher diameter generates more torque at lower rotational speed and vice versa [4]. Also, its angular acceleration increases, whereas the rotor moment of inertia decreases with a growth in the aspect ratio [8].

In order to reveal an influence of the aspect ratio on the Savonius rotor performance, a set of numerical simulations was conducted. A classical Savonius rotor equipped in two semi-circular buckets and endplates was studied for its aspect ratio in the range \( AR = 0.5 - 5 \). Power coefficient changes and the accompanying flow structure were analyzed as well as.

Apart from the aspect ratio defined above, two dimensionless numbers are used here to describe the Savonius rotor performance for different wind conditions, i.e., a power coefficient:

\[
 Cp = \frac{T \omega}{0.5 \rho v^3 A}
\]

and a tip speed ratio:

\[
 TSR = \frac{\omega R}{v}
\]

where: \( T \) – torque, \( \omega \) – angular velocity, \( R \) – radius of the rotor, \( \rho \) – air density, \( v \) – far field wind velocity, and \( A \) – rotor projected area (H-D).

2. Definition of simulations

Three-dimensional 3D numerical models of a classical Savonius rotor equipped in two semi-circular buckets with an overlap gap and endplates were studied. Its main dimensions are shown in figure 1. Different values of the turbine aspect ratio were achieved by modification of the turbine height. Taking advantage of the constant section of the rotor and the flow symmetry, its lower half was considered only. A computational domain layout and main dimensions are presented in figure 2. The computational space was divided into two domains. The internal, cylindrical one contained the space around the rotor and it was surrounded by an external, rectangular domain. The external space was divided into two parts to simplify mesh generation, especially when a blockage effect was investigated.

![Figure 1. Main dimensions of the Savonius rotors.](image1)

High quality hexahedral meshes of flow fields around the turbines were generated in ANSYS Meshing with a sweep method in all regions. The mesh refinement in the vicinity of rotor blades and endplates (with the first nodes at the wall \( y^+ < 1 \) ) allowed one to fully resolve the flow in boundary layers. The endplate refinement was extended to the rotor surrounding (i.e., in the part of the external...
domain bounded by the orange box in figure 2) in order to properly resolve the flow in shear zones. Taking into account low changes in flow parameters in the zone far away from the rotor, the mesh outside the orange box was coarsened towards the domain boundaries. The same mesh layout was applied in the planes perpendicular to the rotor axis, however, a number of nodes along the turbine axis was adjusted with respect to the rotor height. Thus, depending on the aspect ratio, the mesh was composed of 8.8 – 13.0 millions of nodes.

Transient simulations of flows in the Savonius rotors were conducted with ANSYS CFX 18.2. 360 time steps per one rotor revolution were selected for all the cases under consideration, thus, the Root Mean Square of the Courant number was RMS Cu = 12 – 15. A further decrease in the time step did not affect the simulation. Due to fact that the Mach number Ma < 0.1, the air was assumed to be incompressible. As indicated above, the computational space was divided into two domains. The internal, cylindrical one (surrounded by the light blue interface in figure 2) was rotating with a constant angular velocity according to the specified tip speed ratio. The external, rectangular domain was stationary. Dimensions of this domain were selected on the basis of numerical tests in such a way that the blockage effect was negligible. Thus, a series of tests for different blockage was conducted for the rotor with AR = 1.5 and for TSR = 0.8. The outcomes of this study are presented in figure 3. A domain for the rotor projected area equal to 0.5% of the domain cross-section was selected for further investigations. In this case, the Cp value differed less than 0.5% from the value estimated for the blockage → 0.

The Shear Stress Transport turbulence model, which was successfully applied in the previous simulations of the Savonius rotor [9], [10], [11], was used. No significant difference was obtained for simulations with other turbulence models/methods (SAS SST and DES) conducted for TSR = 0.8. Preliminary tests revealed that modeling of a transition in the boundary layer has a low impact on the solution results, therefore, the fully turbulent flow was solved. At the domain inlet, the wind velocity of 4 m/s (Reynolds number based on the rotor diameter Re_D = 2.6·10^5) as well as the low turbulence intensity (1%) and the turbulent to molecular viscosity ratio equal to 1 were imposed. At the outlet, the static pressure equal to the atmospheric one was selected. A half of the rotor was solved, thus, the symmetry condition was applied in the middle of the rotor height. The blade and endplate walls were assumed to be smooth. A transient rotor-stator interface was applied at a transition between the internal and external domain. Two blocks of the external domain mesh were connected by means of the General Grid Interface.

![Figure 3. Power coefficient as a function of the domain blockage.](image3.png)

![Figure 4. Numerical simulation results versus the experimental data.](image4.png)
Second order time and space discretization schemes were applied. Typically 5 – 8 internal iteration loops were required to reach the prescribed Root Mean Square residual target RMS RES = 1·10^{-5} (good solution quality) for each time step. In the majority of cases, the simulations were conducted for 6 – 8 rotor revolutions. It was sufficient to keep the averaged power coefficient Cp changes in the subsequent rotations below 0.1%. However, for TSR ≥ 1.0, the period-averaged value of Cp varied, thus, a higher number of revolutions (10-12) was necessary to average the data.

The simulation results were verified against the experimental data [12]. In the experiment, the natural size Savonius rotor with the dimensions specified in figure 1 and AR = 1.5 was tested under open field conditions. In order to compensate the effects of disturbances due to changes in the wind speed and direction, only the data for wind conditions constant in periods longer than 30 s were taken into account. The power coefficient characteristics of experimental and numerical simulation results are shown in figure 4. A good agreement was reached for the TSRs close to optimal, i.e., for TSR = 0.8 – 0.9, a relative difference with respect to the trend line of the experimental data did not exceed 5%, and it was within 15% for TRS = 0.7 – 1.0. It is not clear if high differences for low (TSR < 0.7) and high (TSR > 1.0) are due to numerical or experimental reasons. Further experimental and numerical studies are planned. However, an agreement for the TSRs close to optimal is sufficient for the needs of this study.

3. Discussion of the results

Three-dimensional 3D numerical simulations of flows in Savonius rotors with aspect ratios in the range AR = 0.5 – 5.0 were conducted for the tip speed ratio TSR = 0.8. A characteristics of the power coefficient Cp for the investigated aspect ratios is presented in figure 5. An increase in Cp with a growth in AR can be observed, but its intensity changes around AR = 1.5. For AR < 1.0, the power coefficient increases rapidly, similarly as presented in [7] and [5]. On the other hand, for AR > 2.0, changes in the coefficient are much less considerable. The 2D simulation result marked in figure 5 with a dashed line indicates the limit of Cp (for AR = ∞). A decrease in the power coefficient with a decrease in the aspect ratio is due to boundary layer effects near the endplates as well as the deflection of a part of the air stream beyond the endplates [7]. Both these effects are very strong for low aspect ratio rotors. With an increase in AR, the relative effect is wakening, but reminds important.

![Figure 5](image5.png)  
**Figure 5.** Power coefficient as a function of the aspect ratio for TSR = 0.8.  
![Figure 6](image6.png)  
**Figure 6.** Power coefficient as a function of the TSR for different aspect ratios.
Additional simulations were conducted for different values of TSR in the case of rotors with AR = 0.5, 1.5 and 5.0. Characteristics of Cp for the investigated AR are presented in figure 6. The results clearly indicate that the tip speed ratio for the maximal power coefficient (Cp_max) increases with a growth in the aspect ratio. For AR = 0.5, the power maximum was reached for TSR = 0.8, whereas for AR = 5.0, it increased to TSR = 0.90 – 0.95. Thus, for AR > 1.5, the maximal values of Cp are slightly higher than the values presented in figure 5 (for TSR = 0.8). Such changes were not present in [5] and [6], whereas some shift of Cp_max towards higher TSR can be found in [7] and [13]. Also in [3], some impact of AR on TSR for Cp_max can be seen. However, limited data available for different Savonius rotor configurations do not allow one to draw clear conclusions.

The friction of endplates consumes a part of the power generated by rotor blades. For all cases under study, almost the same value of power consumption was obtained. Thus, if this value was related to the power output of the turbine, a contribution of friction losses for the low aspect ratio rotors was high. As one can see in figure 7, it exceeded 10% for rotors with AR < 0.75, whereas for AR > 1.5, it was lower than 4%. In all cases, the external side of the endplate was responsible for approximately 70% of the friction torque. However, this assessment of the endplate friction did not take into account effects of the boundary layer development and flow displacement at the blade tips.

A turbine rotor is a kind of obstacle (bluff/blunt body) which deflects the wind. Due to its specific shape, the Savonius rotor displaces a significant fraction of the wind volume flow rate. The aspect ratio of the rotor influences this displacement as shown in [7]. In figure 8, period-averaged values of the relative air flow indicate the displacement intensity. Data was gathered in the regions located on the plane perpendicular to the wind flow direction and placed on the rotor axis. Rotor flow (1.2xD) and Rotor flow (2xD) data sets indicate the ratios of wind flow rates through the rectangular regions of the rotor height and the width of 1.2 and 2 rotor diameters to the inlet flow rates through the same size regions. Only 30% of the wind stream flew through the region of 1.2xD, whereas this value increased up to 60% if the region was stretched sideways one diameter each side (2xD). A slight decrease in the relative flow rate through these regions were observed with a decrease in AR. The majority of the displaced wind flew behind the endplates (Displacement Endplates data set). Only a small fraction of the fluid was displaced sideways (Displacement Sides data set) for the lowest aspect ratio rotors (less than 5% for AR ≤ 0.75), however, this share increased to 30% for the highest aspect ratio under study AR = 5.0.
4. Conclusions
The aim of this study was to investigate an influence of the aspect ratio of the Savonius rotor on its performance. Transient, 3D numerical simulations of classical Savonius rotors equipped in two semicircular buckets with an overlap gap and endplates were studied for the aspect ratio $AR = 0.5 - 5.0$. The numerical model was verified against the experimental data and a good agreement was reached for the tip speed ratios close to optimal. A blockage effect was studied and an appropriate domain size was chosen.

A continuous increase in the power coefficient with a growth of the aspect ratio of the Savonius rotor was observed. Significant changes were present for low aspect ratios ($AR < 1.0$), whereas for higher aspects, an increase was lower. 2D simulation results indicated that the power coefficient would still increase for $AR > 5.0$. However, due to some structural reasons, an application of high aspect ratio Savonius rotors is difficult. Therefore, rotors with $AR = 1.0 - 2.0$ seem to be a good compromise between the rotor performance and compactness.

The effect of wind friction at the endplates was almost the same for all aspect ratios. Thus, a decrease in the power coefficient for low aspect ratio rotors was due to a deflection of higher fraction of the wind stream beyond the rotor (mostly beyond the endplates) and relatively higher thickness of boundary layer zones at the blade tips. The tip speed ratio for the maximal power coefficient was TRS = 0.8 at the lowest aspect ratio under study and it increased up to $TSR = 0.9 - 0.95$ for the highest aspect ratio.

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