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Experimental and numerical analysis of vaned wind turbine performance and flow phenomena

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A B S T R A C T

One feature in the ongoing energy transition is that the energy is more often produced close to its final utilizer. The operated device should be reliable to use and it should not annoy the people. Also, the size of the power production module may have limits that are not to be exceeded. One of the solutions is to use vaned Savonius turbines with a low-solidity vane design. It provides a relatively small physical size with low flickering and noise emissions, in addition to its improved starting behaviour in low winds. However, the performance of such a turbine is not well documented in the relevant literature and its internal flow physics are not well known. From this background the current study presents an experimental test case, coupled with validated numerical simulations, for a vaned Savonius turbine and performs what is so far the most complete fluid dynamic analysis of its performance and flow phenomena. The key novelties are that separate experimental and numerical results are presented with and without the stator in order to study the stator-rotor interaction, including accurate static pressure measurements inside the turbine. In addition, a general flow model is presented.

1. Introduction

Microscale distributed energy generation close to the end user is one of the trends in the energy sector that is part of the global energy transition. Wind turbines are among the key technologies in low-carbon societes, however, there are challenges which slow its utilization. Usually, in discussions turbine noise is considered to be one of the most important reasons if not the most important reason for resistance against this technology. Additionally, people have other concerns, for example visual disturbance due to flickering. Fortunately, these challenges can be tackled with the engineering approach.

The turbine type that is chosen can influence the sound emission. Since the noise of the wind turbine is directly proportional to the tip-to-speed ratio (TSR) a lower value usually leads to lower sound pressure levels. In this respect, the Savonius turbine is superior to both H-rotor or horizontal axis wind turbines (HAWTs) due to its lower operating TSR. It is also worth mentioning, that vertical axis wind turbines (VAWTs) are less sensitive to the highly changing wind conditions than HAWTs are, as discussed (e.g. by Pope et al. [1]), thus favoring their use in densely populated urban areas.

A simple way to decrease the visual annoyance due to flicker is to use a vane system around a VAWT which closes or restricts the visual connection to the rotor. The design of the vanes can also have great influence on the overall turbine performance. Shahizare et al. [2] studied an omnidirectional guide vaned H-rotor and their numerical results predicted that both power and torque coefficients were improved when an open rotor was surrounded by a vane system with optimal solidity. In another study Shahizare et al. [3] examined the effect of guide-vane angle on the setup, which was found best in terms of performance in their previous study. As a result, it was shown that the vane angles have a marked influence on turbine performance. In this work, they also presented experimental power coefficient data as a function of TSR. Their numerical results also indicated that the guide vanes are able to accelerate the flow velocity above the free-stream values. Additionally, Pope et al. [1] presented a Zephyr turbine concept which includes nine vanes with and without reverse winglets and five Savonius-type blades. The results indicated that reverse winglets do not improve the

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Nomenclature

A	rotor swept area [m^2]
C_P	power coefficient [−]
Δp	relative pressure [Pa]
R	radius [m]
T	torque [Nm]
V_x	axial velocity
V_{inf}	free-stream velocity [m/s]
y^+	non-dimensional wall distance [−]
ρ	density [kg/m^3]
ω	angular speed [rad/s]

Subscripts

in	before the porous domain
out	after the porous domain

Abbreviations

CFD	computational fluid dynamics
HAWT	horizontal axis wind turbine
MP	measurement point
RANS	Reynolds-averaged Navier-Stokes
RMS	root mean square
TSR	tip-to-speed ratio
VAWT	vertical axis wind turbine

turbine power. Nobile et al. [4] performed a numerical analysis on a three-bladed H-rotor which was covered with symmetrical stator vanes. Their study suggested an improvement of both power and torque coefficients when the vane system was included. It was also shown that the turbine torque stays positive with optimal vane setting angles.

Various successful efforts are presented in the literature to improve the performance of Savonius turbines by guiding the incoming flow into the advancing blade and simultaneously reducing the flow that would interact with the returning blade. The first known published work using flat plate shielding was published by Alexander and Holownia [5] who showed an improvement in turbine efficiency when compared to a non-shielded case. Tartuferi et al. [6] presented a successful study where they used a self-orienting curtain system to improve the experimentally verified power and torque coefficients over a wide range of TSRs. Also, Altan and Atilgan [7] found a positive influence of using a curtain in front of the rotor in a study that included both experimental and numerical analyses. Long curtains were found to outperform shorter ones. When Mohamed et al. [8] used an obstacle shield in front of the returning blade for a two-bladed Savonius turbine their numerical data suggested improved performance compared to a non-shielded design. They also found that the turbine was capable of self starting at any angular rotor position. Additionally, Irabu and Roy [9] tested a guide box around two- and three-bladed Savonius turbines, which improved the power coefficient by 1.5 times compared a three-bladed turbine without a box. It was also discussed that the three-bladed design should be able to self start at any angular position, which was not the case with the two-bladed design.

The positive influence of the vanes, improving the self-starting capability of turbines, has been also mentioned by other researchers. Chong et al. [10] presented an experimental and numerical study where an omnidirectional guide vane was introduced into a H-rotor and reported that a H-rotor's self-start wind speed was decreased from 7.35 m/s to 4 m/s. Additionally, Chong et al. [11] and [12] studied the influence of non-symmetric guide vanes on Sistan wind turbine performance and it was discussed that the turbine was not able to restart without the vanes.

One of the drawbacks of vaned turbines is that the flow downstream of the rotor can be negatively affected. This problem was mentioned by Takao et al. [13] when they discussed that guide vanes downstream of the rotor negatively influence rotor airflow. To overcome the mentioned challenge they proposed an upstream guide vane row with three vanes. As a result of their study, it was experimentally shown that the performance of a three-bladed H-rotor can be improved for most of its operating range.

To the authors' knowledge there is currently only one research article that presents pressure measurements inside the vane passages and none include the rotor. Burlando et al. [14] studied a non-omni-directional design with three vanes in a wind tunnel and performed steady Reynolds-averaged Navier-Stokes (RANS) simulations. Also, multihole-probe measurements were conducted at one radial location inside the stator and one outside the turbine. Their results show that the flow outside the vanes is accelerated above free-stream velocity when the flow goes past the turbine but no velocity gains are expected for their design in the area where the rotor would locate.

Although the general trend in the studies has been that the performance of a vaned vertical-axis wind turbine is better than that of the typical vaneless design, it is worth noting that the turbine size increases due to vane installation. This fact is important to acknowledge since in urban energy production the physical size can be an important factor in the decision-making process. From the presented point of view the vane ring outer diameter should be kept as small as possible, and to avoid flickering problems, the solidity should be relatively high with short chord lengths. In the case of omnidirectional design, it also means that the negative influence of the downstream vanes on performance cannot be avoided.

From the presented background it can be concluded that the current body of knowledge lacks of information about the influence of the stator-rotor interaction in different parts of the turbine. A better understanding of this phenomenon could open new avenues for further performance improvements. Also accurate measurements inside the turbine are required in order to understand the internal flow physics and also to provide test cases for code validation. To answer these research gaps, this work presents what is so far the most complete fluid dynamic analysis of both the flow phenomena in and performance of a vaned Savonius turbine. The key novelties are:

1. The influence of stator-rotor interaction is examined from fluid dynamic and performance points of view.
2. A test case is presented for model validation, including separate results with and without a rotor.
3. A generic flow model for a vaned Savonius turbine is presented.

Also, the cases with the stator only are not constrained into presented rotor type and they can be used to guide the design processes with different rotors in the future.

The turbine design is presented first to explain its specific features and main design parameters. This is followed by sections discussing the experimental setup and the used modelling methods. The accuracy of the numerical model without the rotor is examined next, including a comparison with the vane ring pressure measurements and evaluation of the vane performance. In the second to last section, before the conclusion, the influence of the stator-rotor interaction is investigated both in average and transient conditions. Also the accuracy of the full turbine model is evaluated.