

Experimental Investigation on a Mini Hibrid Wind Turbine

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Abstract

The proposed work concerns an experimental investigation of the aerodynamic of a hybrid mini wind turbine which couples the main characteristics of classical mini wind turbine Darrieus and Savonius. The study consisted in the investigation on a prototype of hybrid turbine characterized by a geometry Darrieus with 4 fixed blades and two Savonius blades, positioned internally at the Darrieus, constituted by flexible wings which vary in their extension, reducing the extension at the increase of the angular velocity to wrap completely when the angular speed is such high to allow the wing profiles of Darrieus to generate a positive torque. In order to characterize the hybrid turbine, the flow field was investigated by means of a bidimensional Particle Image Velocimetry (PIV) technique, measuring velocity and vorticity in two aerodynamic configurations (Savonius blades at the maximum extension and at 2/3 of the maximum extension), for two flow conditions, i.e. 5 and 10 m/s, and for two angular velocity of the turbine which correspond at a tangential maximum velocity of 1 and 1.7 m/s. The measurements were performed in a wind tunnel with a measurements test section of approximately 400 x 400 mm and a maximum speed as high as 30 m/s.

Keywords: PIV measurements, Small Size Wind Turbine, Darrieus Turbine, Savonius Turbine.

INTRODUCTION

The need to exploit renewable energy sources has led to a strong development of wind turbines capable of recovering energy from fluid streams naturally present in the atmosphere. This development was based mainly on the development of large wind turbines with rotors that can reach thirty meter in diameter and an elevate aerodynamic efficiency but they can be installed in dedicated fields. Small turbines (mini wind turbines) has been developed in order to utilize the wind energy usually in isolated locations where is necessary to have a small footprint and a relatively low efficiency is tolerable. In such category must mention the Savonius and Darrieus turbines. The two types of turbine are both vertical axes, the Savonius is composed of semi-cylindrical shape blades, the Darrieus, instead, is composed of blades having an airfoil such as to generate a thrust on them oblique aerodynamic forces able to generate a rotation torque.

Since the operating conditions of the Savonius turbines are quite simple and intuitive, in literature it is possible to find a large amount of studies on the functioning characteristics of the Darrieus turbine, which has been the subject of numerous studies observing the behaviour in field [1 - 5] or

experimentally with extensive use of PIV techniques, as reported into the references [6 - 10], or by means of hot wire anemometry like Fereira et al [11]. Also, visualization in a water channel have been adopted by Brochier et al. [12]. Naturally also numerical studies have been carried out extensively as in the cases reported in [13 - 15].

It is well known that the aforementioned turbines have operating parameters diametrically opposed. In fact, the Savonius turbine is a turbine "on resistance" that can generate power even at low wind speed with a high starting torque. The Darrieus turbine, instead, exploits the power generated by the airfoils arranged vertically around the axis of rotation and realize better performance than that obtainable with the Savonius, especially at relatively high angular velocity, but Darrieus turbine has the drawback of not being able to self-start because it needs an initial rotational speed to be added vectorially to the wind speed.

There are already not yet on the market mini wind turbine in hybrid configurations which seek to combine the positive characteristics of the two types of turbines, i.e. the high torque in the starting phase realized by the Savonius turbine and the good performance at high speed shoved by the Darrieus turbine. Unfortunately, this kind of hybrid scheme has the drawback of generating a mutual aerodynamic interference that goes adversely affect the final overall performance.

The original idea of the hybrid turbine under study is therefore to maintain and combine the best features of both types of turbine, but reducing the aerodynamic interference phenomena.

The hybrid impeller, under investigation, is composed by four fixed Darrieus blades, and two internal Savonius blades movable. The Savonius turbine (internal) generate the starting torque and guarantee the operation at low wind speed. As the wind speed increase and the angular velocity of the hybrid turbine reach the regime necessary for putting the Darrieus turbine in the working condition, the Savonius blades are suddenly rewound in order to reduce the aerodynamic interference with the Darrieus blades.

EXPERIMENTAL APPARATUS

Wind tunnel

The study of the hybrid mini wind turbine was made in a low speed wind tunnel specifically designed and installed in the laboratory of Fisica Tecnica Industriale of the University of Basilicata. The tunnel is of the "open circuit" type and is composed by: a 22 kW fan operated with a suitable electronic inverter, by a convergent duct with reduction ratio of the

cross-section equal to 2; by a test section with useful dimension of approximal $0.6 \times 0.6 \times 1.0$ m. In the test section two suited transparent windows (top and side) allowing the optical PIV measurements. Both the aforementioned windows with dimension of 0.5×0.9 m. In order to uniformize the flow and reduce its turbulent level, a layer of honeycomb is positioned before the test section (approximately at 1.5 m upstream).

The maximum attainable air speed is 30 m/s with a value of turbulence intensity as less as 3%. Fig. 1 shows the maximum dimensions of the circuit, while in Fig. 2 a rendering image of the wind tunnel is reported. In Figs. 3 and 4 is respectively possible to observe a typical velocity and turbulence intensity distribution (realized by means of the PIV technique discussed in the next section) obtained for the rated speed of the wind tunnel at 10 m/s.

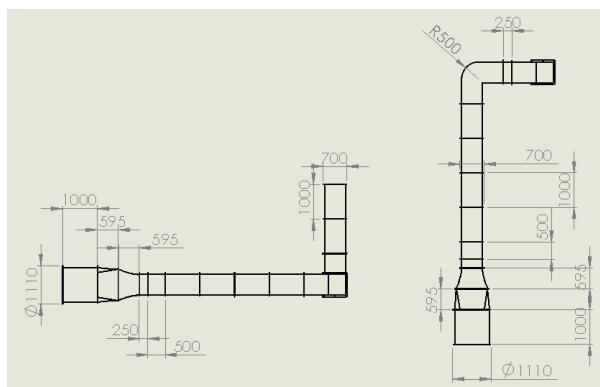


Figure 1. Lay-out and main dimension (expressed in millimeter) of the adopted wind tunnel.

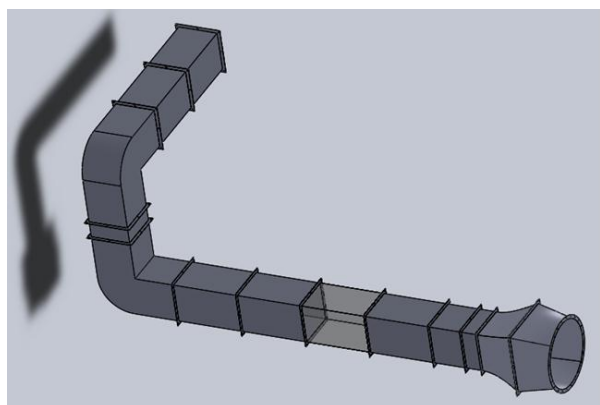


Figure 2. Rendering of the wind tunnel. The fan (not present in the image) is connected to the circular flange visible on the right side of the image.

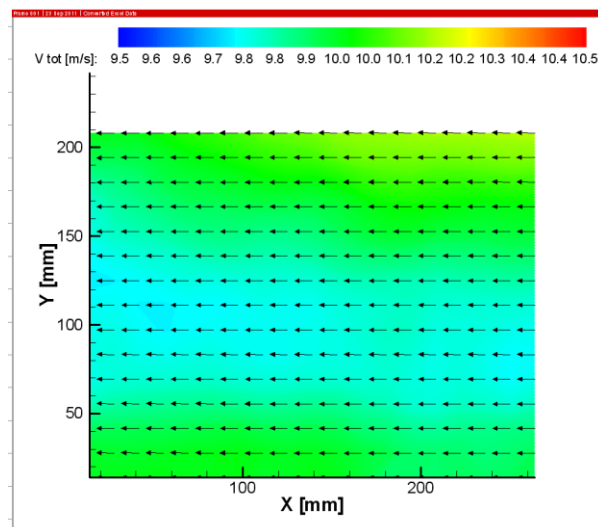


Figure 3. Velocity distribution for the wind tunnel nominal velocity of 10 m/s

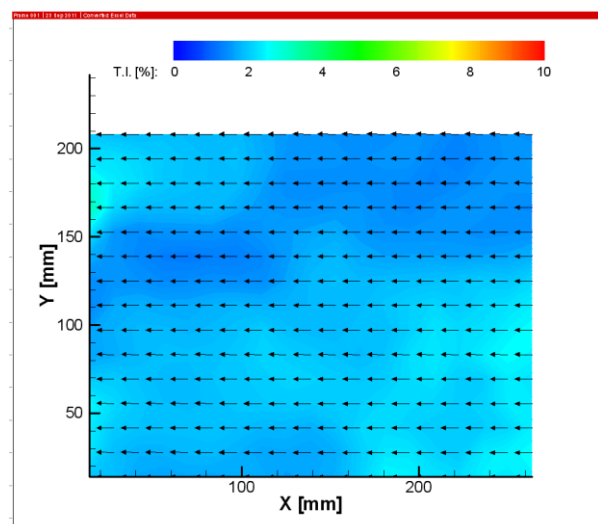


Figure 4. Turbulent intensity for the wind tunnel nominal velocity of 10 m/s

Particle Image Velocimetry (PIV)

A PIV system has been employed to analyze the instantaneous behavior of the velocity field. The adopted system (whose layout is reported in Figure 2) is based on two pulsed Nd:YAG lasers firing on the second harmonic (green 532 nm). The beams, properly separated in time, are recombined on the same optical path by a polarized dichroic filter. Then the beams are expanded in one direction, by a combination of spherical (negative) and cylindrical lens, to obtain a 100 mm wide and 0.3 mm thick laser sheet in the measuring region. The laser sheet is used to illuminate the airflow around the turbine blade. An air assisted spray has been used to atomize silicon oil in small droplets seeding in wind tunnel upstream the test section.

The images have been collected by means of a double frame 1024 x 1024 pixels PCO CCD camera synchronized with the

two laser beams and with the frame grabber by means of a dedicated electronic synchronizer. The images are formed by two different layers, each of them containing information about the seeding positions obtained by firing one of the two lasers. So, the initial seeding positions (first laser beam, image on the first layer) and the final one (second laser beam, image on the second layer) are spotted.

The images were then post-processed by means of the TSI Insight V.3.2 software in order to extract the sub-images formed by 32 x 32 pixels from each layer, and to perform a cross-correlation between the two corresponding sub-images. An interrogation algorithm extracts the correlation peak position from the cross-correlation domain with a sub-pixel precision, and performs the calculation of the two velocity components for those sub-images, by a pixel-to-mm conversion factor. Interrogations are repeated using a recursive algorithm for the entire set of double frames images. The measured velocities are reported in a grid with size of 32 x 32 pixels with a 50% overlap (Nyquist criteria). The two laser beams have been fired at about 100 mJ per pulse (second harmonic), and with separation time of 140 ms. In Figure 5 a schematic lay-out of the adopted PIV is reported.

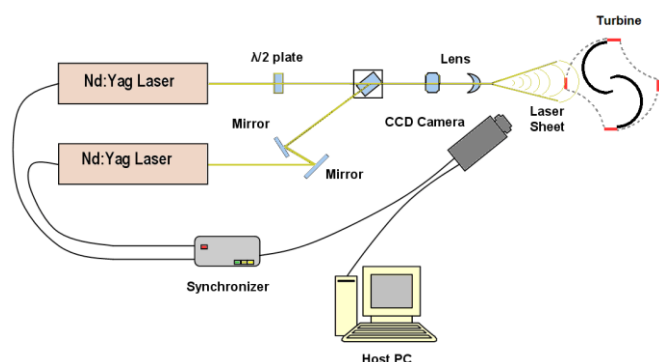


Figure 5. Layout of the adopted PIV technique.

The two-dimensional velocity data have been utilized in order to calculate the vorticity (ω) distribution according with:

$$\omega = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \quad [1]$$

EXPERIMENTAL CONDITION

The experimental investigations were carried out on a model of hybrid turbine appositely realized and consisting on four blades (made of milled plywood) with aerodynamic profile of Darrieus type (Figure 6, airfoil NACA 0015) and two internal blades of Savonius type. In Figure 7 a detail of the hybrid turbine is reported with, in evidence, the Darrieus blades at the maximum extension, realized in acrylic transparent material in order to allowed optical measurements (PIV). The Savonius blades can be easily removed and substitute with blades of different extension. In practice the experiments have been performed for the Savonius blades at their maximum extension (Figure 7) and for an extension of 2/3 of the maximum (Figure 8). In order to perform optical

measurements, the rotation axis is positioned horizontally instead of vertical, as in the real turbine. The external diameter of the turbine is equal to 0.3 m while the length of the blades is approximately 0.31 m (Figure 9). The hybrid turbine is maintained in rotation by a stepping motor visible in left part of Figure 7.

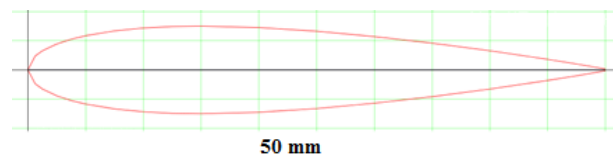


Figure 6. Airfoil NACA 0015

The flow conditions to which has been exposed the turbine have been two: the first equal to 5 m/s, when the Savonius blades were at maximum extension; the second equal to 10 m/s, with the Savonius blades at 2/3 of their maximum extension. In the two configurations, the turbine has been placed in rotation with a peripheral velocity of 1.0 m/s, for a flow velocity as high as 5 m/s, and 1.7 m/s, for a flow velocity as high as 10 m/s.

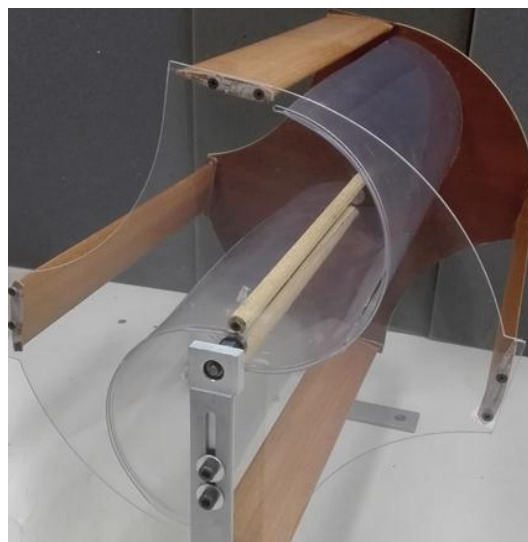


Figure 8. Image of the investigated hybrid turbine Darrieus-Savonius



Figure 8. A detail of the investigated hybrid turbine Darrieus-Savonius, with the Darrieus blades at 2/3 of the maximum extension.

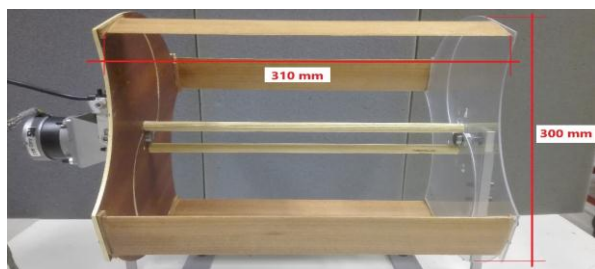


Figure 9. Main dimension of the investigated turbine

EXPERIMENTAL INVESTIGATION

The experimental investigations have been performed in a region, around the blades, as show in Figure 10 and Figure 11. In particular Fig 10 shows the investigated area comprising the blades of both turbines, whereas in Figure 11 the investigated area comprises only the Darrieus blade, because the Savonius blade is reduced in the extension (blade extension only 2/3 of the maximum extension). The PIV data are collected always in the same positions, i.e. the turbine is rotate of an angle of 30° respect the normal at the direction of the flow. In order to activate this the PIV system is synchronized with the rotation of the turbine by means on a shaft encoder mounted on the rotation shaft.

The analysis of the first zone (Figure 10), allowed to detect the interaction of the two blades varying the gaseous flow speed (and turbine angular speed) when changes the extension of the Savonius blades.

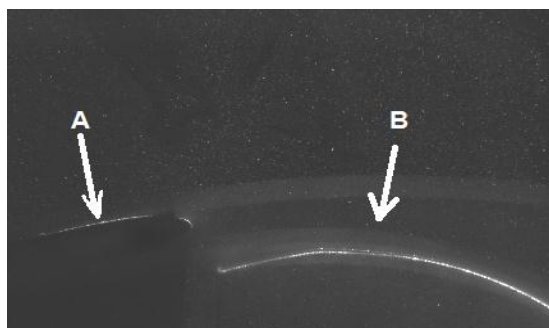


Figure 10. Investigated zone (not processed PIV image) in which it is possible to see the Darrieus blade (A) and the Savonius blade (B).

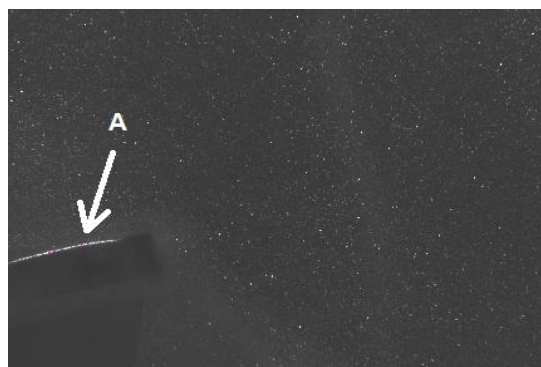


Figure 11. Investigated zone (not processed PIV image) in which it is possible to see only the Darrieus blade (A) because they Savonius blade is at 2/3 of the maximum extension.

In the area reported in Figure 11 it is possible to observe the investigated region around the Darrieus blade affected by the presence of the reduces extension of the Savonius blades.

The measurements have been performed in two main conditions: for a flow field of 5 m/s and a tangential velocity of the turbine of 1 m/s; flow field of 10 m/s and tangential velocity of the turbine of 1.7 m/s in the case of reduced presence of the Savonius blades.

RESULTS AND DISCUSSION

Starting from the analysis of the flow field near the Darrieus blade with the Savonius blades at their maximum extension (configuration shown in Figure 10), it is possible to observe how the flow field is profoundly altered even at low flow velocity (5 m/s) and at low turbine rotation speeds (peripheral speed of 1 m/s). This is observable in Figure 12 in which the velocity distributions are reported showing a very low intensity of the air velocity around the blades. Also, the vorticity, reported in Figure 13, shows the formation of a not organized flow.

The flow field (Figure14) and the vorticity (Figure 15) become much more regular in the condition of the Savonius blade retracted to an extension of 2/3 of the maximum extension.

The aerodynamic situation highlighted in the previous configuration recurs even in the case of speed of the undisturbed flow at 10 m/s and turbine tangential speed as high as 1.7 m/s.

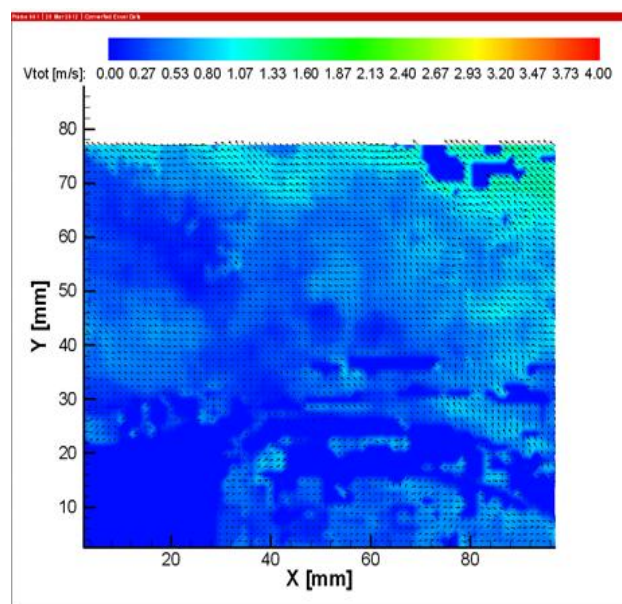


Figure 12. Flow field around the two blades (Savonius at maximum extension) main stream at 5 m/s, turbine tangential velocity 1 m/s.

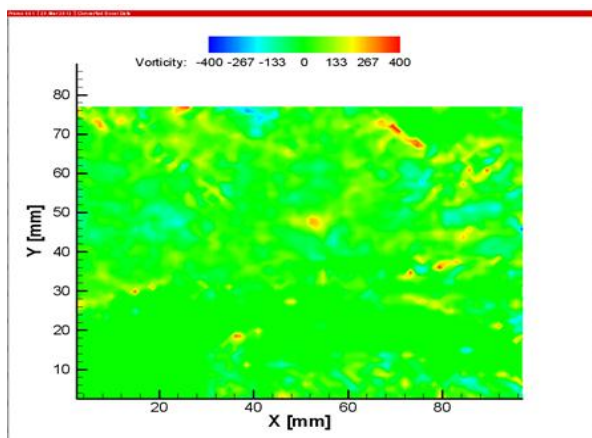


Figure 13. Vorticity ω around the two blades (Savonius at maximum extension) main stream at 5 m/s, turbine tangential velocity 1 m/s.

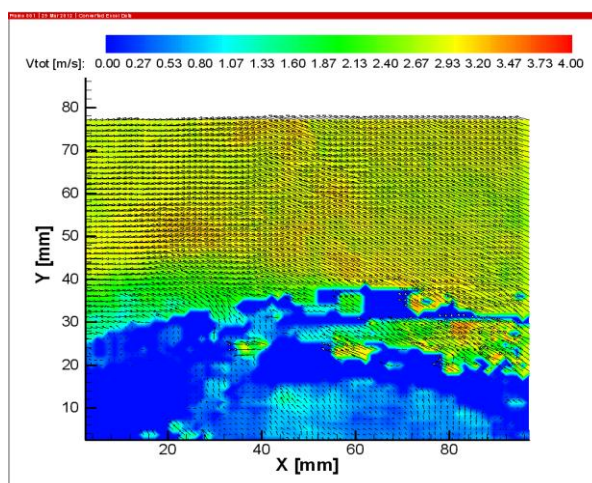


Figure 14. Flow field around the two blades (Savonius at 2/3 of the maximum extension) main stream at 5 m/s, turbine tangential velocity 1 m/s.

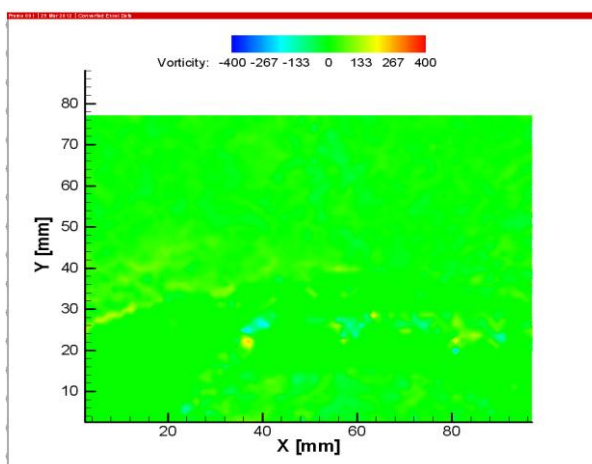


Figure 15. Vorticity ω around the two blades (Savonius at 2/3 of the maximum extension) main stream at 5 m/s, turbine tangential velocity 1 m/s.

In fact, the velocity distribution shown in Fig 16, obtained with the Savonius blades at maximum extension, indicates a strong reduction of air velocity (velocity distribution at the top left of Fig 16) much lower than the air velocity in the right part of Fig 16 (flow region away from the Darrieus blade).

The vorticity distribution reported in Figure 17 shows the same phenomena.

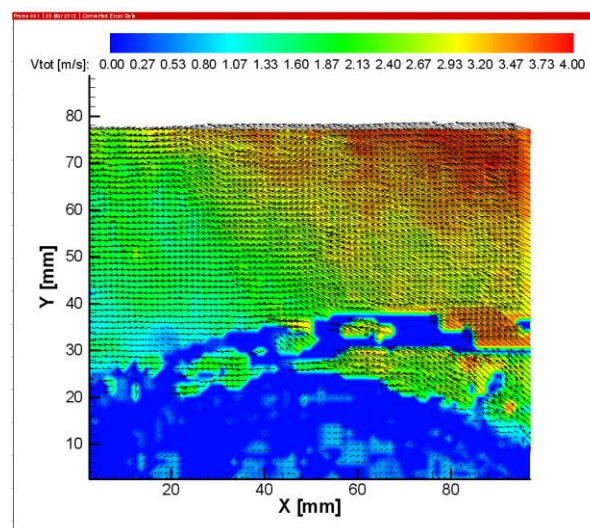


Figure 16. Flow field around the two blades (Savonius at the maximum extension) main stream at 10 m/s, turbine tangential velocity 1.7 m/s.

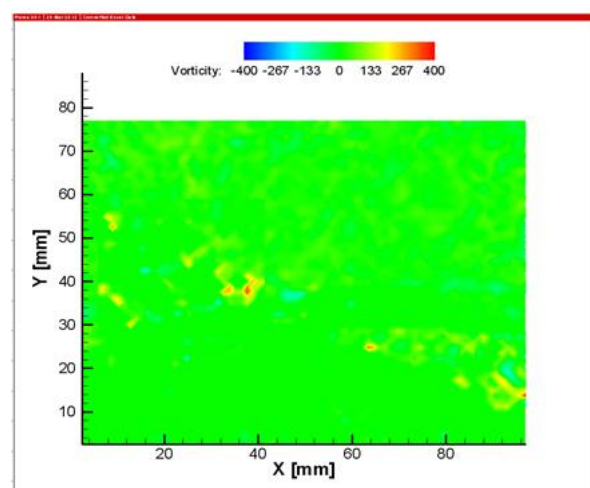


Figure 17. Vorticity ω around the two blades (Savonius at maximum extension) main stream at 10 m/s, turbine tangential velocity 1.7 m/s.

The extension reduction of the Savonius blades to 2/3 of the maximum value shows, in the case of undisturbed flow at 10 m/s, a flow field with a substantially greater uniformity even with perturbed flow, precisely in the region of the leading edge of the Darrieus blade (Figure 18). Also, the vorticity

distribution, reported in Figure 19, shows a major uniformity of the flow.

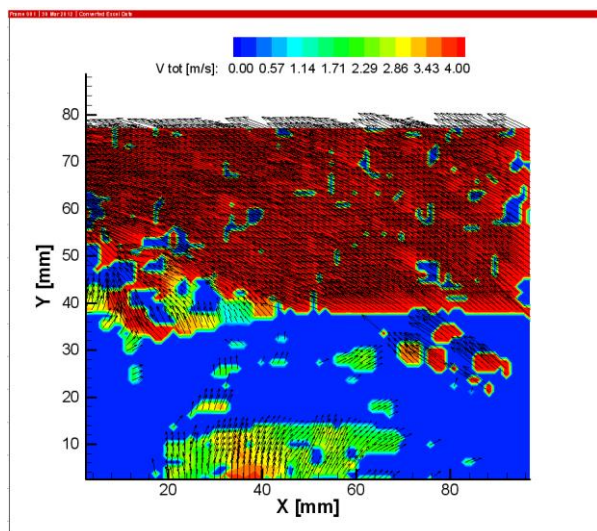


Figure 18. Flow field around the two blades (Savonius at 2/3 of the maximum extension) main stream at 10 m/s, turbine tangential velocity 1.7 m/s.

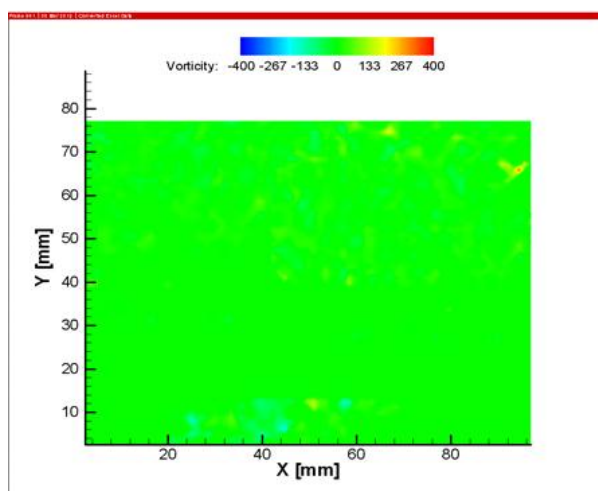


Figure 19. Vorticity ω around the two blades (Savonius at 2/3 of the maximum extension) main stream at 10 m/s, turbine tangential velocity 1.7 m/s.

Moving on the analysis of the Darrieus blades not directly concerned with the presence of the Savonius blades (configuration shown in Figure 7) and observing, for brevity, only the condition of undisturbed flow equal to 10 m/s with tangential velocity of the turbine as high as 1.7 m/s, it is possible to observe how the presence of the Savonius blades in both configurations continues to disrupt the flow as visible in Figs. 20 and 21 (blades at maximum extension) and in Figs. 22 and 23 (blades at 2/3 of the maximum extension).

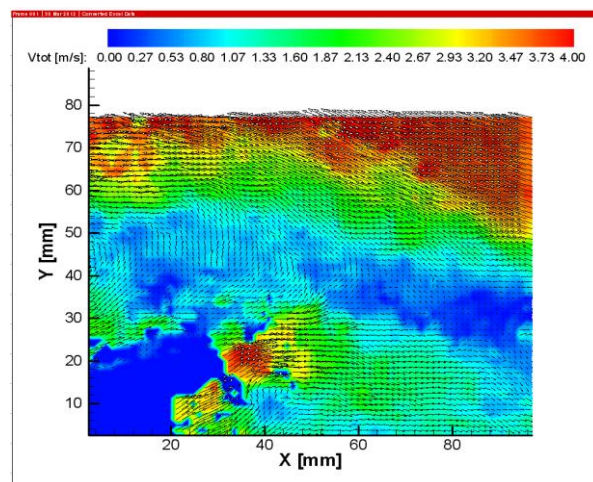


Figure 20. Flow field around the two blades (Savonius at the maximum extension) main stream at 10 m/s, turbine tangential velocity 1.7 m/s.

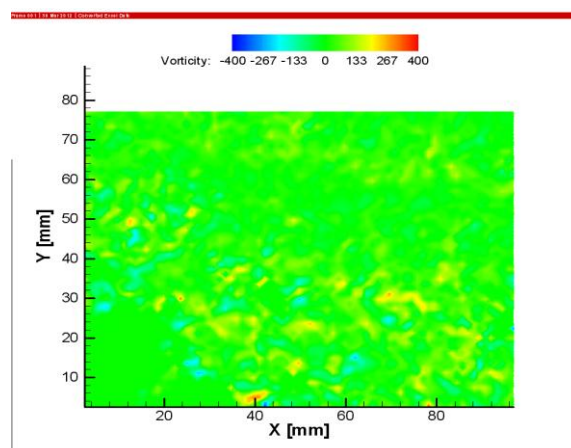


Figure 21. Vorticity ω around the two blades (Savonius at maximum extension) main stream at 10 m/s, turbine tangential velocity 1.7 m/s.

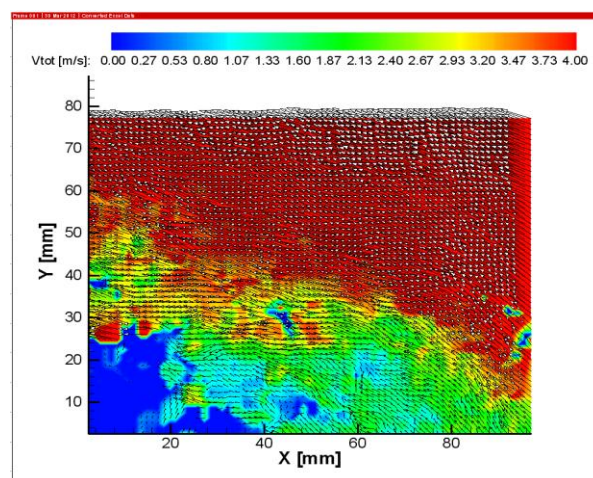


Figure 22. Flow field around the two blades (Savonius at 2/3 of the maximum extension) main stream at 10 m/s, turbine tangential velocity 1.7 m/s.

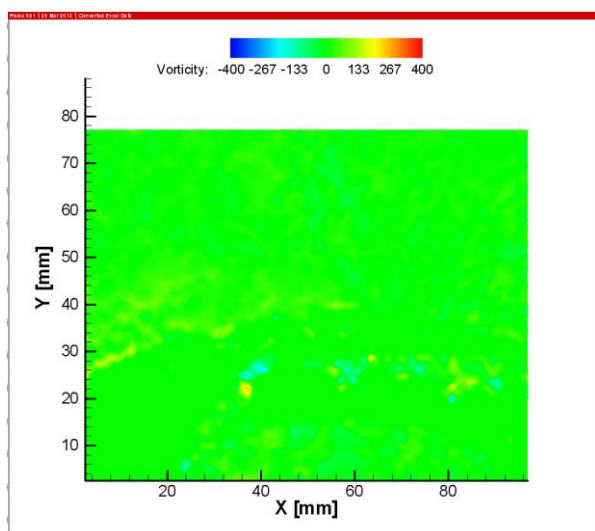


Figure 23. Vorticity ω around the two blades (Savonius at 2/3 of the maximum extension) main stream at 10 m/s, turbine tangential velocity 1.7 m/s.

CONCLUSIONS

The experimental investigations, performed on the hybrid turbine, seems to demonstrate that the presence of the Savonius blades significantly alters the flow field around the hybrid turbine and this happens specially in the neighbourhood of the Darrieus blades, at least into the proposed configuration, in which two Savonius blades are positioned inside four blades of a Darrieus turbine. A partial reduction of the extension of the Savonius blades, while improving the flow distribution, do not eliminate the problem. This effect is more visible when the turbine is exposed ad a low velocity flow field (5 m/s) than at a high velocity flow field (10 m/s), but it's still present. Since the Darrieus turbine needs to be brought at a relatively high rotation speed, the Savonius turbine can serve the purpose only if, at the end of its task, an appropriate mechanism can be able to rewind the Savonius blades so quickly to avoid a significant slowdown of the rotation speed of the Darrieus turbine. i.e. "stall" of the turbine.

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