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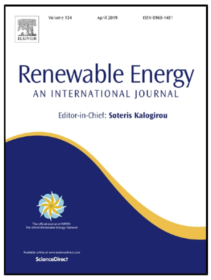

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The effect of strong ambient winds on the efficiency of solar updraft power towers: A numerical case study for Orkney

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Abstract

Solar updraft tower (SUT) is a simple power plant in which ventilation of heated air inside a channel drives a turbine. This system is recognised as suitable for areas with abundant solar radiation. As a result, there is no extensive research on the performance of SUTs under mild solar radiation. Studies show that strong ambient crosswinds can affect the performance of a SUT. In this paper, the efficiency of SUTs in areas which benefit from strong winds, despite low solar radiation, is investigated through numerical modelling. Comparison is made between the efficiency of a commercial-scale SUT in Manzanares (Spain) with intensive solar radiation, and one of the same size potentially located in the windy and mild climate of Orkney Islands in Scotland. The results show that ambient crosswinds can increase internal air speed and efficiency of a SUT by more than 15% and 50%, respectively. Consequently, such a SUT in Orkney can offer more than 70% of the efficiency of the one in Manzanares. The results show that, for a given power capacity, a wind turbine enclosed in a SUT can be considered as an alternative to a number of conventional wind turbines installed at height in the open air.

Keywords: solar updraft tower; ambient wind; efficiency; solar chimney; wind turbine.

1. Introduction

Solar power, as a renewable source of energy, is currently generated using Photovoltaic panels or by adopting solar thermal techniques. SUT is a simple thermal power plant designed to generate electricity on a large scale. It generally consists of a collector, a tower and a turbine (Figure 1). Solar radiation passes through a greenhouse collector located around a vertical channel/tower. This increases the temperature of the air and the ground below the collector and reduces the air density. To reach a balance in temperature, the ground periodically transmits the absorbed heat to the air below the collector (e.g. in night times). The difference in the density of the air under the collector and outside the tower creates a buoyancy air flow inside the tower and rotates the turbine mounted at the lower entry to the tower. This rotation is transmitted to a generator producing electricity.

The idea of SUT (also called solar chimney) was first proposed in the late of 1970s [1]. About eight years later, building a 50KW SUT began in Manzanares, Spain. That solar tower had a height of 194.6m, a diameter of 10m, and a collector radius of 122m, with an air velocity of 15m/s generated inside the tower to drive the turbine. After construction of that prototype, several large-scale SUTs were established, including a 200MW power plant with a tower height of 1000m and a collector diameter of 7000m in Mildura, Australia, or a 40MW power plant with a tower height of 750m and a collector diameter of 2100m in Ciudad Real, Spain [2, 3].

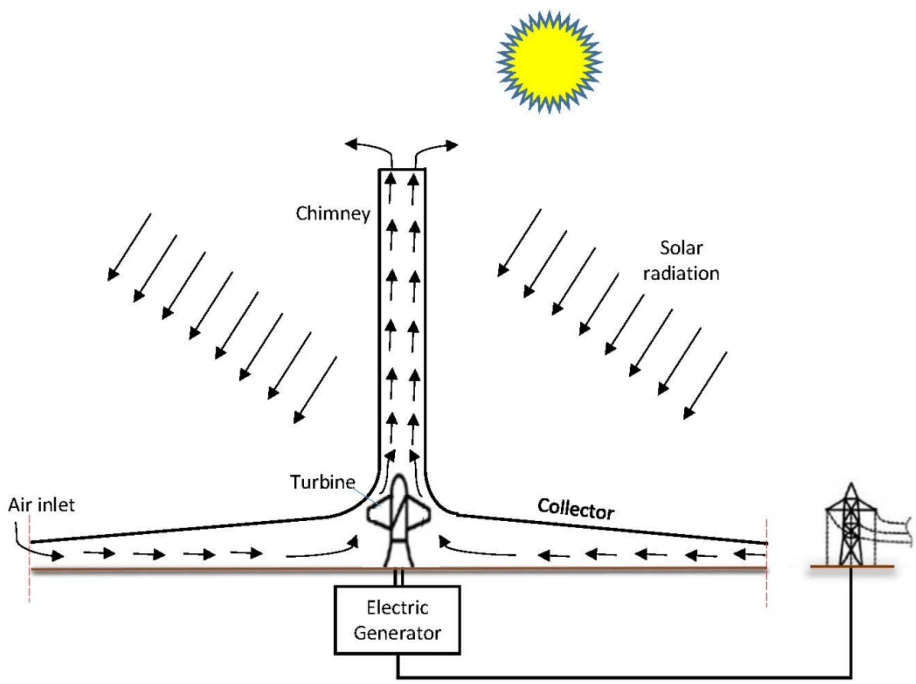


Figure 1 Schematic overview of a solar updraft tower

To date, many researchers have investigated the efficiency of SUTs affected by various factors. Mullet offered a method for calculating the overall efficiency of them [4]. Haaf investigated design range and optimal dimensions for various power productions [1, 5]. Padki and Sherif examined the effect of operational and geometric parameters such as tower height and the ratio of input and output areas on the performance and efficiency [6, 7]. Yan et al. developed a comprehensive analytical model for obtaining equations of air flow, air velocity, power output, and energy efficiency [8]. Pasurmarthi and Sherif showed that SUT is a good technology in hot climate regions such as Florida and examined the impact of air temperature and air velocity on power generation, through theoretical and experimental studies [9, 10, 11].

A SUT does not need direct sunlight and can operate under a cloudy sky by exploiting the diffused solar radiation [12]. However, this system is traditionally recognised for its higher efficiency in areas with abundant solar radiation. As a result, there is no extensive research on the performance of this system in areas with mild solar radiation. Nevertheless, the effect of ambient winds on the efficiency of SUTs has been investigated by some researchers [13, 14, 15, 16, 17, 18].

The existing studies show that strong ambient crosswinds can positively affect the performance of SUTs [13, 14]. A research conducted by Zhou and Xu in 2016 revealed that wind can influence the performance of SUTs in three main ways; 1) by heat loss from the collector roof to the environment, 2) by blowing the indoor heated air to the outside of the collector instead of up through the tower and 3) by producing a suction effect through the tower outlet. The first two effects decrease the efficiency and the last one increases it [13]. Ming et al. in 2012 showed that weak ambient crosswinds reduce the efficiency due to blowing the heated air to the outside of the collector, while strong winds increase the efficiency due to a suction effect at the tower outlet [14]. Studies conducted by Serag-Eldin in 2004 revealed that wind effects are definitely not negligible, although this effect is generally neglected in the analysis of SUTs [15, 16]. That study showed that wind can deteriorate the performance of SUTs in case the height of collector inlet is large. However, Ming et al. (2013) proved that a blockage which is circularly set a few meters away from the collector inlet can eliminate that negative effect [17]. Pretorius in 2004 showed that strong ambient winds result in an increased power output due to a pressure rise at the tower outlet [18].

In this paper, the potential and the efficiency of producing electricity using SUTs in areas which benefit from strong winds, despite low solar radiation, is studied via a numerical case study for Orkney Islands in Scotland. The aim is to investigate how strong and steady winds can improve the performance of a SUT and make it a suitable option for not-too-sunny but windy weather conditions.

For this purpose, a model in the size of Manzanares power plant is numerically simulated in ANSYS Fluent software [19]. Comparison is made between the performance of this power plant if located in the windy and mild climate of Orkney and the performance of the real power plant in the climate of Manzanares with intensive solar radiation. The parameter representing the performance of the SUT is the air speed inside the updraft tower.

2. Numerical Modelling

Flow in a SUT is developed because of air buoyancy. For a large SUT, such as the Spanish sample, a turbulent air flow is formed inside the channel due to the geometric aspect ratio of it [20]. Therefore, the standard k-ε turbulent model is used with the standard wall function to describe the flow of the power plant [12]. For this purpose, 4 sets of equations are used: Continuity equation, Navier–Stokes equations, Energy equation, and k-ε equations [12]. For discretization of the equations, the Second Order Upwind method is applied, and equations are solved in steady state conditions using ANSYS Fluent software [19].

The values of the constants used in the standard k-ε model are listed in Table 1.

Table 1 Values of the constants used in the standard k-ε model

Cmu	0.09
C_1-ε	1.44
C_2-ε	1.92
TKE prandtl number	1.0
TDR prandtl number	1.3
Energy prandtl number	0.85
Wall prandtl number	0.85

2.1 Geometry of the Model

A SUT with the geometric dimensions of Manzanares power plant is modelled. The geometric characteristics of the model are given in Table 2.

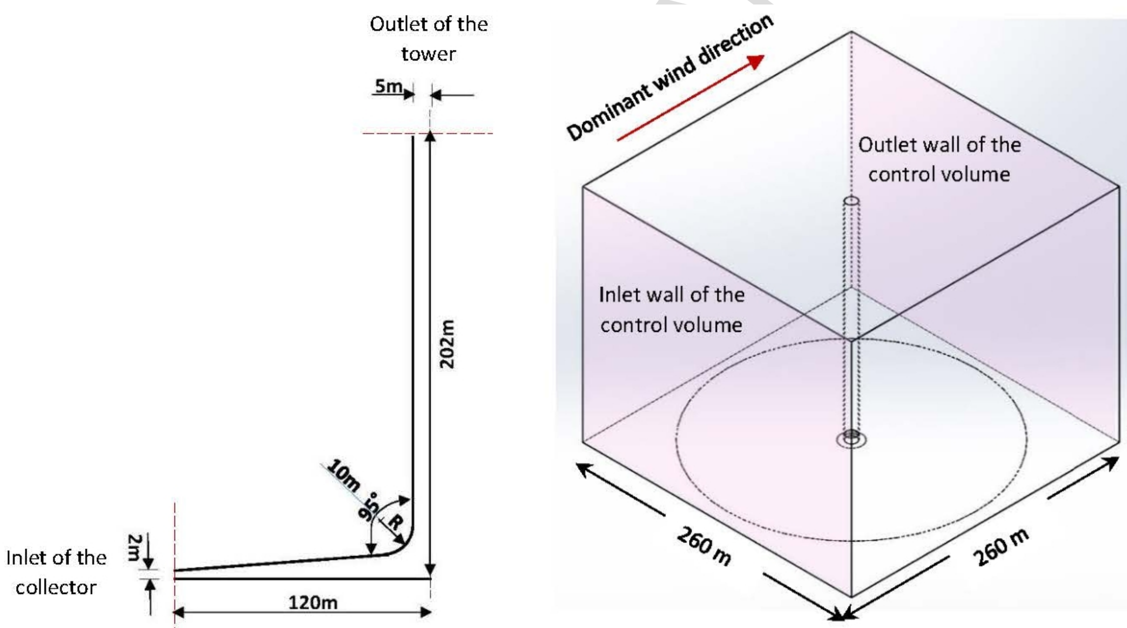
Table 2 Geometric characteristics of the model

Total height	202m

Collector radius	120m
Tower radius	5m
Collector's inlet height	2m
Collector's slope	5°
Collector/ Tower fillet radius	10m

A 3D model is developed to evaluate the effect of ambient wind velocity on developing a suction effect through the outlet of the tower or the inlet of the collector. Those effects are applied to a 2D axisymmetric model (which is numerically a less expensive model) to study the performance of the SUT with and without the suction effects resulted by the ambient wind. The computational cost of the 2D model is 8.3 times less than the 3D model.

Figure 2(a) shows the geometric characteristics of the 2D axisymmetric model. The control volume for the 3D model is illustrated in Figure 2(b). The wind velocity is a vector quantity, with a dominant direction at a time. In the control volume of the 3D model, the inlet/outlet boundary walls are assumed perpendicular to the dominant wind direction. However, the suction effect resulted by the ambient wind at the tower outlet is a scalar quantity that only has magnitude and no other characteristics. It means that applying the magnitude of the suction at the outlet of the 2D axisymmetric model, as the effect of wind, can be accurate enough for the purpose of this study (considering that the geometry of the SUT is simulated in the 2D axisymmetric model exactly the same way as in the 3D model).



(a) (b)

Figure 2 (a) The geometric characteristics of the 2D model; (b) the 3D model

The magnitude of the suction is obtained from the 3D model in which turbulence and wall effects are taken in to account in a purely fluid-dynamic analysis. By applying that suction effect as well as the solar heat flux to the 2D axisymmetric model, a combined thermal and fluid dynamic analysis is carried out.

The wind speed distribution on the inlet wall of the control volume is non-uniform, varying as a function of height, and is given in the following section.

For validation, the 2D model is run for the boundary conditions of the Manzanares power plant and the air speed inside the tower is compared with the same parameter recorded for the real power plant. The results are discussed in Section 3.

It must be noted that, to simplify the numerical modelling, the effect of turbine on the air flow has been neglected in this research. In reality, there are system losses of various components (aerodynamic, mechanical and electrical losses) and these may contribute to the deviation of the actual performance of SUTs compared to the results produced by the numerical methods. Turbine losses are associated with different types of turbine and their installation method. Diffusion losses can also occur after the turbine rotors, where the hub ends, and in the actual diffuser. In multiple turbine configuration, losses may also be generated where the outflow of various turbines merge [21]. However, previous studies show that, with designing the flow passages in an appropriate manner, the aerodynamic losses can be kept low [22]. Considering the above factors in the numerical modelling is beyond the scope of this research. Therefore, the effect of turbine on the internal air speed is not taken into account, in order to avoid complication and considering that this is a comparative study.

2.2 Environmental and Boundary Conditions

Orkney Islands located off the northeast coast of Scotland is known for its strong and constant winds. The annual temperature distribution in Orkney is shown in Figure 3 [23].

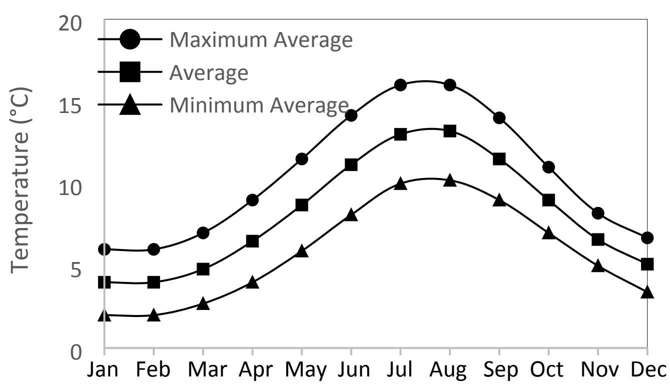


Figure 3 Annual temperature distribution, in Orkney

There is less than 10 °C difference between the average summer and winter temperatures (mild winters with average temp of 5-6°C, and low summer temp with an average of 15°C and a maximum of 19°C) [23].

For the environmental and geographic conditions of Orkney, the solar heat flux is estimated to be 450W/m². To estimate this value, an online Numerical Weather Model (Solar Calculator) has been used [24]. This model can compute potential solar radiation (direct and diffuse irradiance) for various geographic locations, for clear skies. The input values for this numerical model include geographical latitude, geographical longitude, altitude, temperature, and relative humidity. The estimations in this paper are based on the average annual temperature and humidity.

Figure 4 shows that the average daily wind speed varies between 5.3m/s in July and 8.6m/s in February, and the average annual value is 6.9m/s, all at a height of 10m above the ground [23].

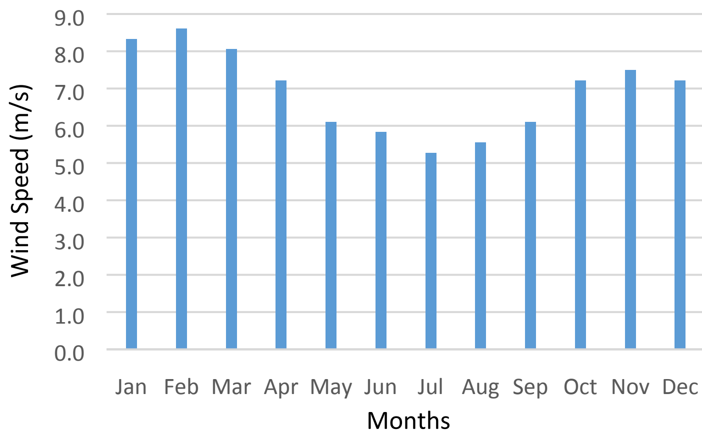


Figure 4 Average daily wind speed for each month, in Orkney

To calculate the variation of wind speed versus height, Eq. 1 can be used, where V_0 is the wind speed (in m/s) at H_0 m above the ground [25].

$$\frac{V}{V_0} = \left(\frac{H}{H_0}\right)^n \quad \text{(Eq. 1)}$$

It is usual to give H_0 the value of 10m, n being a coefficient varying from 0.1 to 0.4 [25]. Assuming the average annual wind speed of 6.9 m/s at a height of 10 m for Orkney, and an average value of 0.25 for n, distribution of wind speed versus height for Orkney can be obtained from Eq. 1, as shown in Figure 5. This distribution is used in the numerical model.

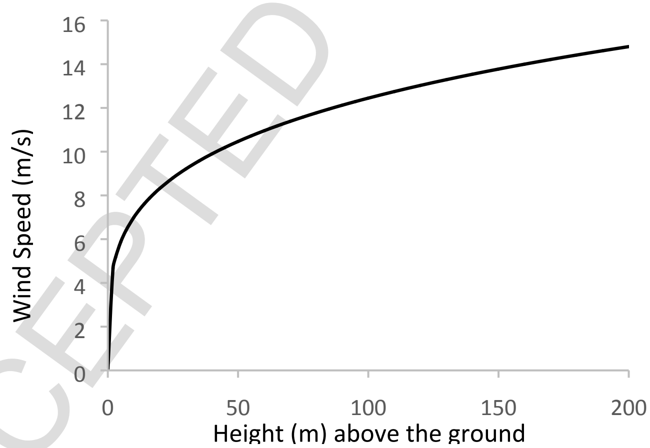


Figure 5 Wind speed distribution as a function of height, in Orkney

For the collector roof which is exposed to the sunlight, a constant heat flux boundary condition is assumed. For the ground, a constant temperature boundary condition is assumed equal to the ambient air temperature. Other walls, e.g. the tower wall, are assumed insulated (zero heat flux for the tower walls, as goiven in Table 3). The convective heat transfer between the air inside and outside the collector is ignored. The magnitudes of the applied boundary conditions are summarised in Table 3, for Orkney's numerical model and Manzanares's SUT.

Table 3. The magnitudes of the applied boundary conditions, for Orkney and Manzanares

Parameters	Orkney's numerical model		Manzanares's SUT
	No wind	With Wind	No wind
Ground/ambient temperature	7° C	7° C	20° C
Collector heat flux	450 W/m²	450 W/m²	1000 W/m²
Tower heat flux	0	0	0
Outlet pressure caused by wind	0	-60 Pa	0

2.3 Mesh sensitivity analysis

To evaluate the sensitivity of the results to mesh size in the numerical modelling, the maximum air speed inside the tower was calculated for a range of mesh sizes for the Manzanares power plant model. Figure 6 shows the results of mesh sensitivity analysis. It can be seen that for a mesh size smaller than 0.1m the average air speed inside the tower converges to the value of 15.1m/s. According to this analysis a mesh size of 0.08m is chosen to ensure that the effect of mesh sensitivity is eliminated in the numerical modelling.

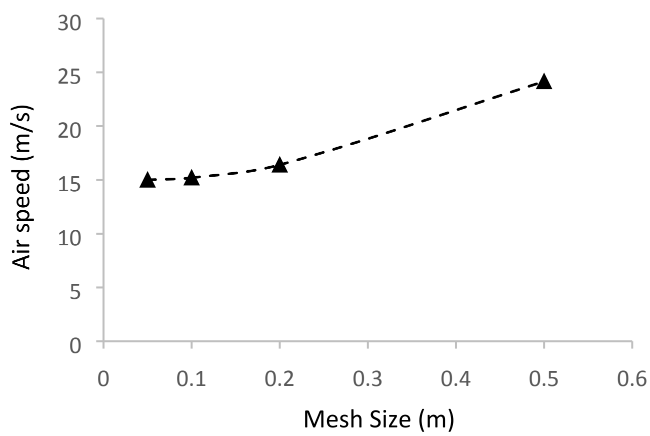


Figure 6 Mesh sensitivity analysis

3. Results and Discussion

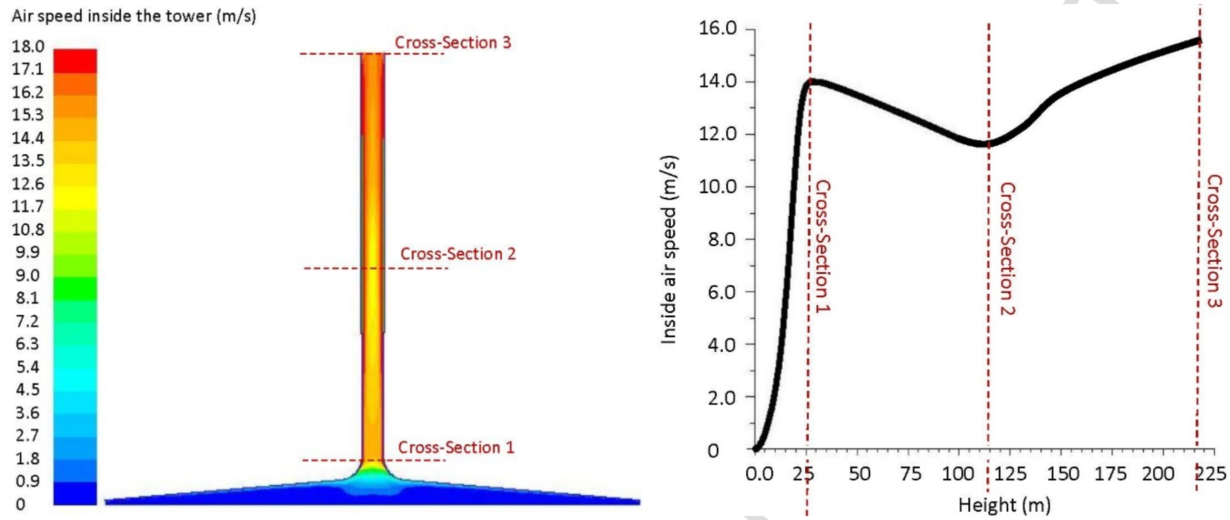
The problem is solved for two different conditions:

1) It is solely the solar heat flux affecting the air velocity inside the tower. In this condition, the expected air speed inside the tower for the numerical model in Orkney is lower than the model of Manzanares, as the solar heat flux is lower in Orkney.

2) The effect of wind is also considered. In this condition, the pressure change at the outlet of the tower in the existence of wind is obtained by solving the momentum equation in the 3D model. The calculations show that a pressure of -60Pa is caused by wind at the outlet of the SUT. The effect of this negative pressure (suction) is added to the effect of solar heat flux in the 2D model.

3.1 Results of the 2D model for Manzanares's SUT

Figure 7(a) shows the contours of air speed inside the tower obtained from the numerical 2D model of Manzanares, and Figure 7(b) shows the variation of air speed on the axis of symmetry along the height of the tower. From this figure a maximum inside air speed of 15.7m/s is developed on the axis of the tower at the outlet section for Manzanares SUT, while the the air speed on the axis of the tower at the inlet section (23m above the ground) is 14m/s .



(a) (b)

Figure 7 (a) Contours of inside air speed for the Manzanares SUT (no wind); (b) Variation of air speed on the axis of symmetry along the tower

From the contours of air speed within the tower, in Figure 7(a), it is seen that the air speed at the edges are higher than the center. That happens as the heat flux passing the collector affects the air adjacent to the collector first. Therefore, the air close to the top surface of the collector has a higher temperature than the interior air. As a result, its density is decreased and its flow speed is increased. That also affects the speed distribution within the tower such that close to the walls the air speed is higher than the center. However, there is still a no-slip condition at the solid boundaries, as the zoomed image below (Figure 8) shows a speed value of zero at the boundaries of the tower.

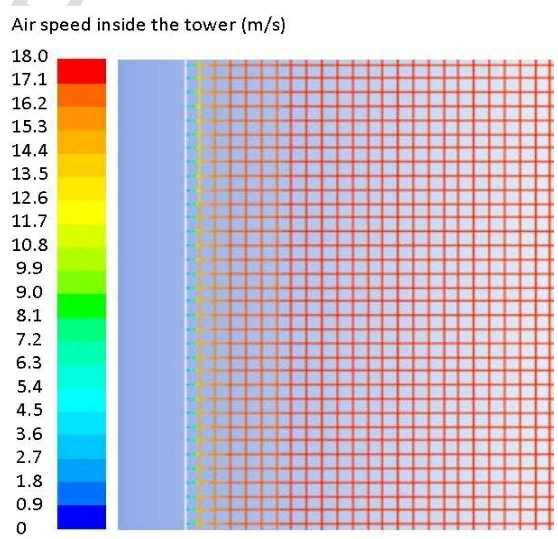


Figure 8 Contours of air speed in close proximity to the boundaries

To understand the variation of air speed inside the tower along the vertical axis and across the diameter, the profile of air speed has been obtained for three different cross-sections shown in Figure 7(a); Cross-Section 1: at the inlet of the tower which is 23m above the ground, Cross-Section 2: at an intermediate section within the tower where the minimum speed is recorded on the axis (see Figure 7(b)), and Cross-Section 3: at the outlet of the tower. These profiles are shown in Figure 9.

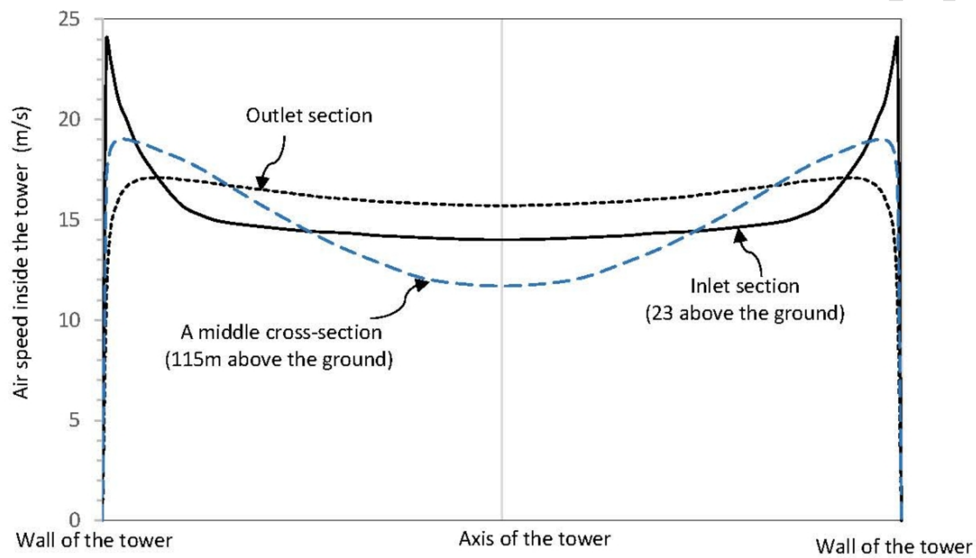


Figure 9 Air speed profiles at different cross sections within the tower, for Manzanares SUT model

In Figure 9 it is seen that, in each cross-section, the air speed at the boundary walls of the tower is zero. It increases sharply reaching the maximum value in close proximity to the boundaries and then drops and varies around the average value within the cross-section. Although the variation of air speed is different for each cross-section, the average air speed within the section is constant for all of them (16.2m/s for Manzanares). That happens, as the air flow in the tower is classified as incompressible (as the Mach number or the ratio of the speed of the flow to the speed of sound is less than 0.3). Therefore, the discharge is constant throughout the tower and that results is constant average air speed for the constant cross-sectional areas through the height of the tower.

For comparison purposes, the inlet section will be looked at, where the turbine is supposed to be installed. The effective air speed on the turbine, is assumed to be the average air speed in the inlet section after excluding the sharp ends of the profile which are very close to the walls (See Figure 10). The weighted area technique is used to calculate the average value.

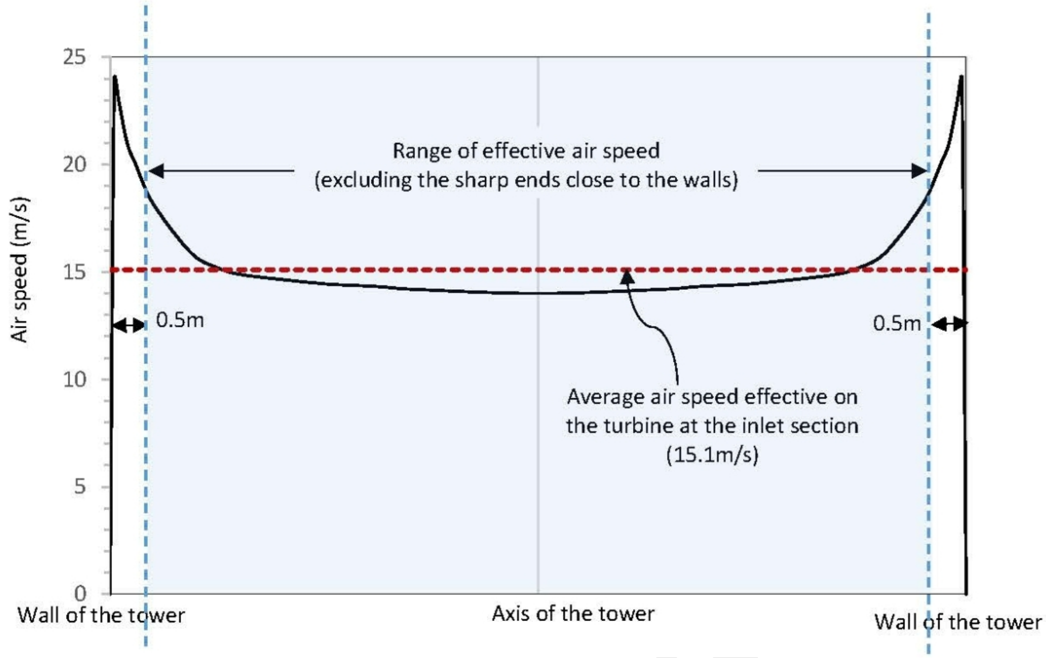


Figure 10 Air speed profile at the inlet section of the tower, and average air speed effective on the turbine, for Manzanares SUT model

Based on the above, the effective air speed from the Manzanares SUT model is 15.1m/s (Figure 10), which is comparable with the value of 15m/s reported for the real Manzanares's project (see Section 1). This can be considered as a proof of credibility for the numerical model. It should be noted that, even without excluding the sharp ends, the average air speed within the whole inlet section is close enough to the real value, to confirm reliability of the model.

In the following sections, the effective air speed obtained from the Manzanares SUT model will be compared with the same parameter calculated from Orkney SUT model with and without taking into account the effect of ambient wind.

3.2 Results of the 2D model for Orkney Islands in the absence of ambient wind

Figure 11(a) shows the contours of inside air speed obtained from the numerical 2D model of a potential SUT located in Orkney in the absence of wind, and Figure 11(b) shows the variation of air speed on the axis of symmetry along the tower. This figure shows that, in Orkney model if the effect of ambient wind is ignored, an air speed of 11.5m/s is developed on the axis of the tower at the inlet section (23m above the ground).

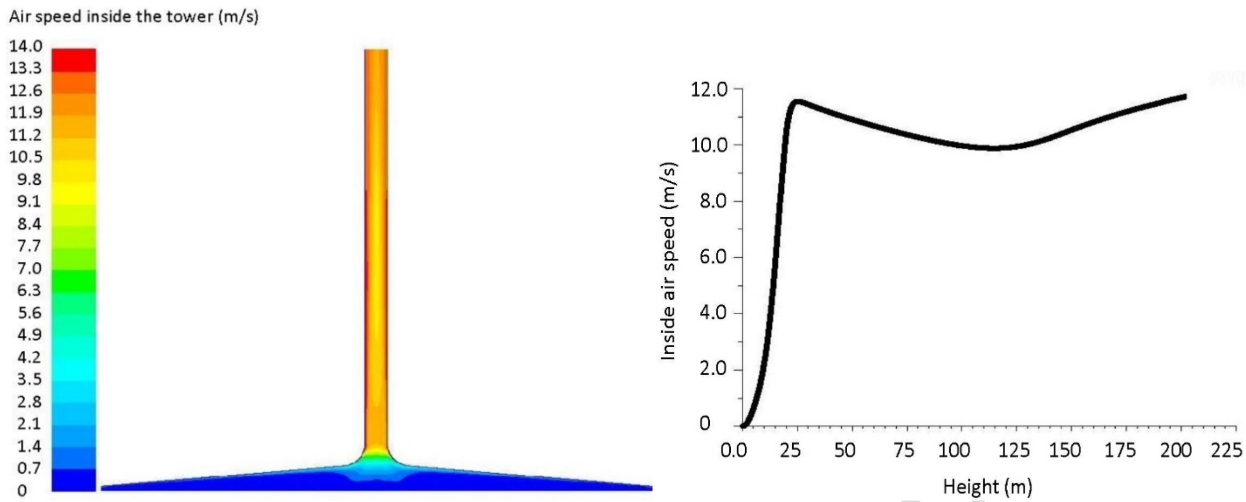


Figure 11 (a) Contours of inside air speed for a potential SUT in Orkney (no wind); (b) Variation of air speed on the axis of symmetry along the tower

Figure 12 shows the air speed profile at the inlet section for Orkney model in the absence of wind. From this figure, it can be seen that the effective air speed is 11.7m/s from that model.

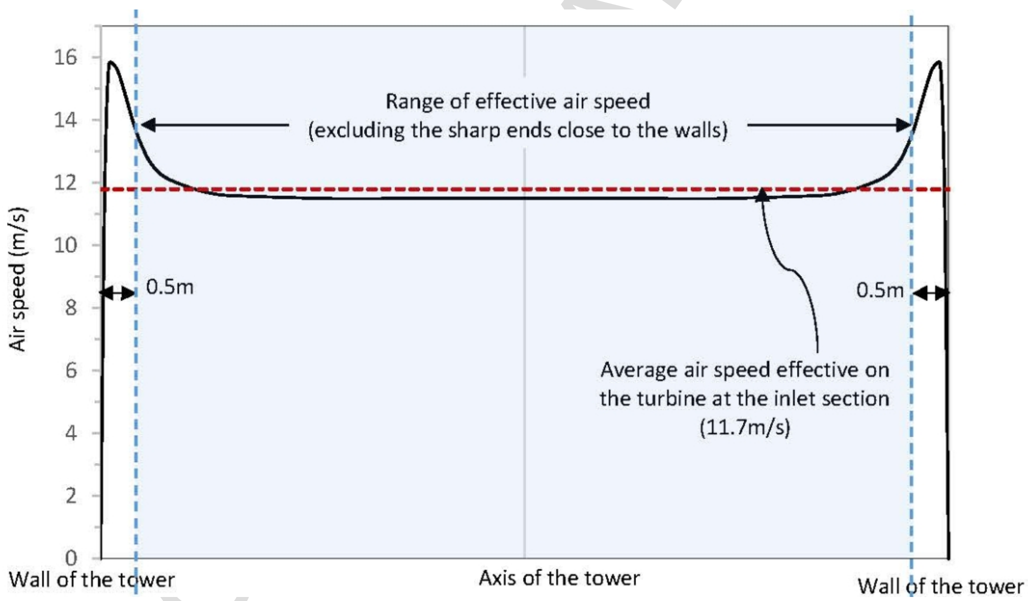
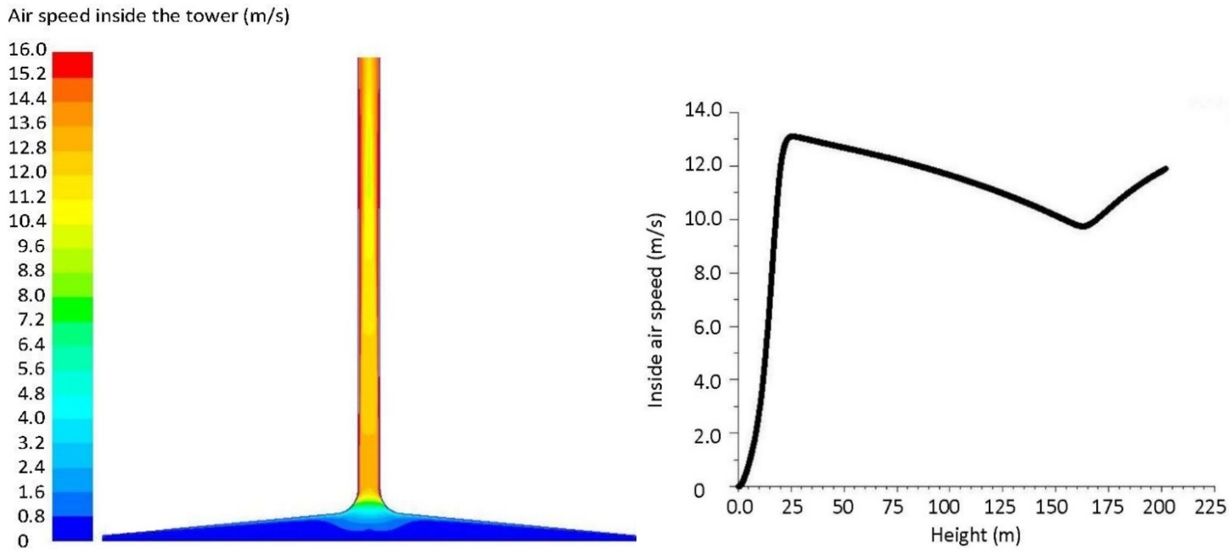


Figure 12 Air speed profile at the inlet section of the tower, for a potential SUT in Orkney (no wind)

3.3 Results of the 2D model for Orkney Islands considering the effect of ambient wind

Figure 13(a) shows the contours of inside air speed obtained from the numerical 2D model of a potential SUT located in Orkney considering the effect of ambient wind, and Figure 13(b) shows the variation of air speed on the axis of symmetry along the tower. This figure shows that, in Orkney model under the effect of ambient wind, an air speed of 13.1m/s is developed on the axis of the tower at the inlet section (23m above the ground).



(a) (b)

Figure 13 (a) Contours of inside air speed for a potential SUT in Orkney under the effect of ambient wind; (b) Variation of air speed on the axis of symmetry along tower.

Figure 14 shows the air speed profile at the inlet section for Orkney model under the effect of ambient wind. From this figure, it can be seen that the effective air speed is 13.5m/s under that conditions.

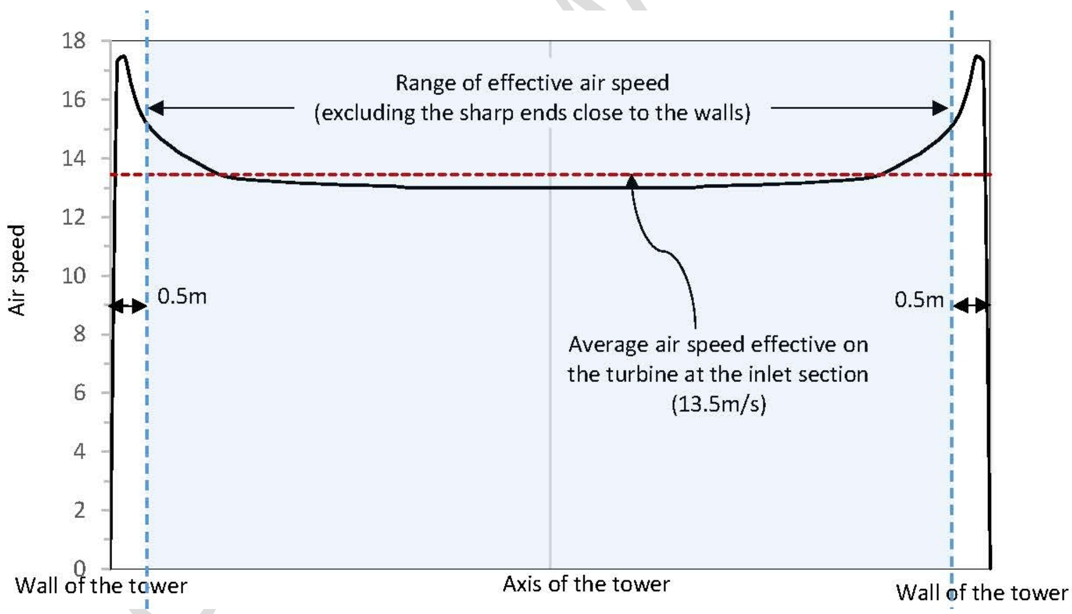
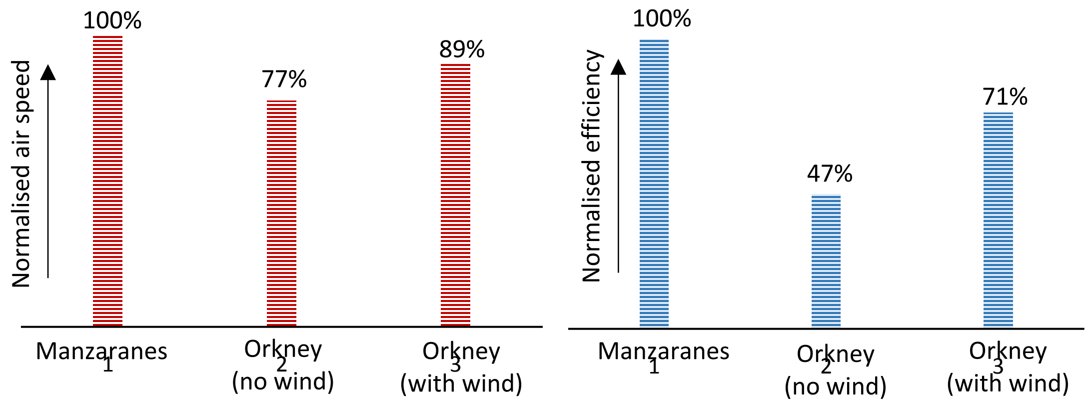


Figure 14 Air speed profile at the inlet section of the tower, for a potential SUT in Orkney under the effect of wind

3.4 Discussion and comparison

In this study, it is assumed that the produced power represents the efficiency of a SUT. The produced power for all wind turbines is proportional to wind speed cubed [26] (in this case the air speed inside the tower cubed). Based on the above findings, a comparison is made between the efficiency of SUTs; one assumed to be in Orkney with and without considering the effect of wind, and one in Manzanares as the benchmark (see Figure 15).



(a) (b)

Figure 15 Comparing the normalized values of (a) effective air speed; (b) efficiency, of the studied SUTs

The results show that, if the effect of ambient wind is ignored, lower solar radiation in Orkney causes 33% reduction in the internal air speed and, as a consequence, 53% reduction in the efficiency of a large scale SUT compared to the one located in Manzanares. However, the effect of strong ambient winds can compensate that reduction to a large extent, such that a large scale SUT in the windy climate of Orkney can have more than 70% of the efficiency of a SUT of the same size located in Manzanares.

However, one may ask in a windy climate like in Orkney what is the need for using a SUT or an air channel to enclose the turbine? In other words, what could be the benefit of a SUT over a wind turbine mounted on top of a tall tower in the open air?

The high air speed is developed in a much lower elevation inside a SUT, if compared with the open air speed (or the ambient wind speed). Figure 16 shows the open air speed in Orkney in comparison with the enclosed air speed inside the SUT and along the axis, as a function of height.

This figure shows that at an elevation of 23m (inlet of the tower) an air speed of 13.1m is generated inside the SUT along the axis. That speed in the open air exists at an elevation of 125m. Therefore, for the same power capacity, installation of the turbine in a lower elevation (e.g. 23m versus 125m) is an advantage for the SUT, which reduces the cost of installation and maintenance of the turbine. From the other side, structural requirements for operation of a wind turbine on top of a tall tower limits the size and the capacity of the wind turbine. It means that, for the same power output, the wind farm concept would need a large number of turbines (smaller size) and towers, while a SUT can generate that power using a single large turbine installed in a low elevation.

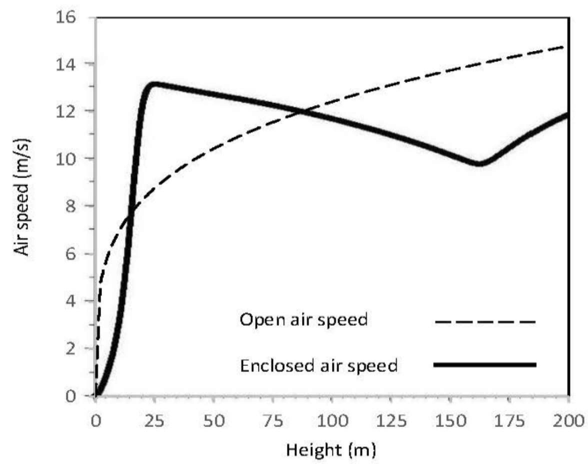


Figure 16 The speed of the air enclosed in the SUT in comparison with the open air speed (ambient wind speed) in Orkney, as a function of height

Furthermore, some studies show that for a given air speed a wind turbine enclosed in a channel can produce higher amount of electricity than a turbine in the open air [27].

The space under the collector can be used as a greenhouse which is ideal for agricultural purposes. This can economically compensate, to some extent, the construction cost of the collector for the SUT option, when it comes to cost/efficiency analysis.

4. Conclusions

The efficiency of a commercial-scale SUT in an area which benefits from strong winds, despite low solar radiation, was investigated through numerical modelling in ANSYS Fluent software. A prototype SUT in Manzanares, exposed to rather intensive solar radiation, was used as a benchmark. Comparison was made between the efficiency of Manzanares's SUT and one of the same size in the windy climate of Orkney Islands, in which the radiation intensity is less than half of Manzanares's. The criterion for this comparison was the air velocity developed inside the SUT.

Based on the findings of this numerical study, strong and steady ambient crosswinds increase the efficiency of a large-scale SUT by more than 50%. Consequently, a large-scale SUT in the windy climate of Orkney can offer more than 70% of the efficiency of one of the same size located in Spain, where the solar radiation is doubled.

The results of this study are based on numerical simulations. Future research is recommended to validate these result using experimental approaches. It would be also valuable to conduct further analysis to determine the effect of various ambient wind speeds combined with the effect of solar heat flux towards the performance of SUTs.

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Highlights:

- Strong ambient crosswinds can increase the efficiency of SUTs by more than 15%.
- A large SUT in a windy climate can have 70% of the efficiency of the one in a sunny climate.
- A wind turbine enclosed in a SUT is more efficient than conventional wind towers.