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TESTING AXIAL FLOW SOLAR CHIMNEY TURBINE USING WIND TUNNEL

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Abstract: The solar chimney power plant (SCPP) is a modernistic and promising technology, which utilizes the combination of solar heating and chimney effect for producing electricity. Solar collector, updraft tower and air turbine are the main components of a solar chimney unit, however, the turbine plays a royal role because it converts the kinetic energy of the heating air into useful mechanical energy. In this study, I measured the power, flow rate, rotational speed and pressure drop of the designed and industrial turbines within the wind tunnel, and the power coefficient of the turbines are calculated by measured values. The turbine was designed according to the blade element theory modified to consider the surrounding duct. we measured the electric power, flow rate and pressure drop of the turbine, and the power coefficient of the turbine is calculated by measured values. Testing of the designed and industrial turbine within wind tunnel shows that the highest power coefficient of the designed turbine is 0.45, while the highest power coefficient of the industrial turbine is 0.32. The designed turbine produces 28.89% higher than the industrial one.

Keywords: axial turbine, wind tunnel measurement, solar chimney power plant, turbine of SCPP

1. Introduction

The energy system in the entire world is depending on fossil fuel and this fuel has harsh effects on the human environment. Finding alternative sources is an essential issue nowadays, so many researchers focus to develop renewable energy as a way of solving energy issues. The solar chimney power plant is a renewable source, which heats the ambient air by solar radiation inside the solar collector. The updraft tower is located in the center of the collector and increases the kinetic energy of the hot air according to a chimney effect principle, as shown Figure 1. The air turbine is the most important component, it produces beneficial mechanical power by converting the kinetic energy of the hot air and controls the airflow inside the SCPP system that effect on the other system components.

In 1976, M. Simon showed the solar chimney has reasonable economic feasibility for production of the SCPP. Haaf et al. [1] was continuing Simon's work in 1979 by developing the first pilot prototype of SCPP in Manzanares, Spain, which was designed peak output of 50 kW, whereas in fact, the measured output was 36 kW [2]. This pilot plant was testing from the year 1982 to 1989. The most important finding of the prototype is the solar chimney concept has enough technically viable and operated reliably for electricity production. In 2002, Gannon and von Backström [3] redesign the turbine of the Manzanares prototype by using free vortex design, their configuration is a single-stage blade rotor with inlet guide vane. They carried out the experimental test to evaluate the proposed turbine. They conclude the proposed design has a total-to-static efficiency of 77-80% and a total-to-total efficiency of 85-90% [4].

On the other hand, researcher used other theory to design solar chimney turbine. Y Zhou et al. [5] used Wilson theory to propose design for solar chimney with vertical collector. The wind tunnel test was carried out to optimize the number of blades turbine and tip speed ratio of their design. Tingzhen et al [6] designed the wind turbine for MW-graded solar chimney power plant system and investigated their turbine by computational fluid dynamic (CFD). To validate the theoretical results, the CFD simulation model was compared with the experimental results of the Manzanares prototype using similar dimensions.

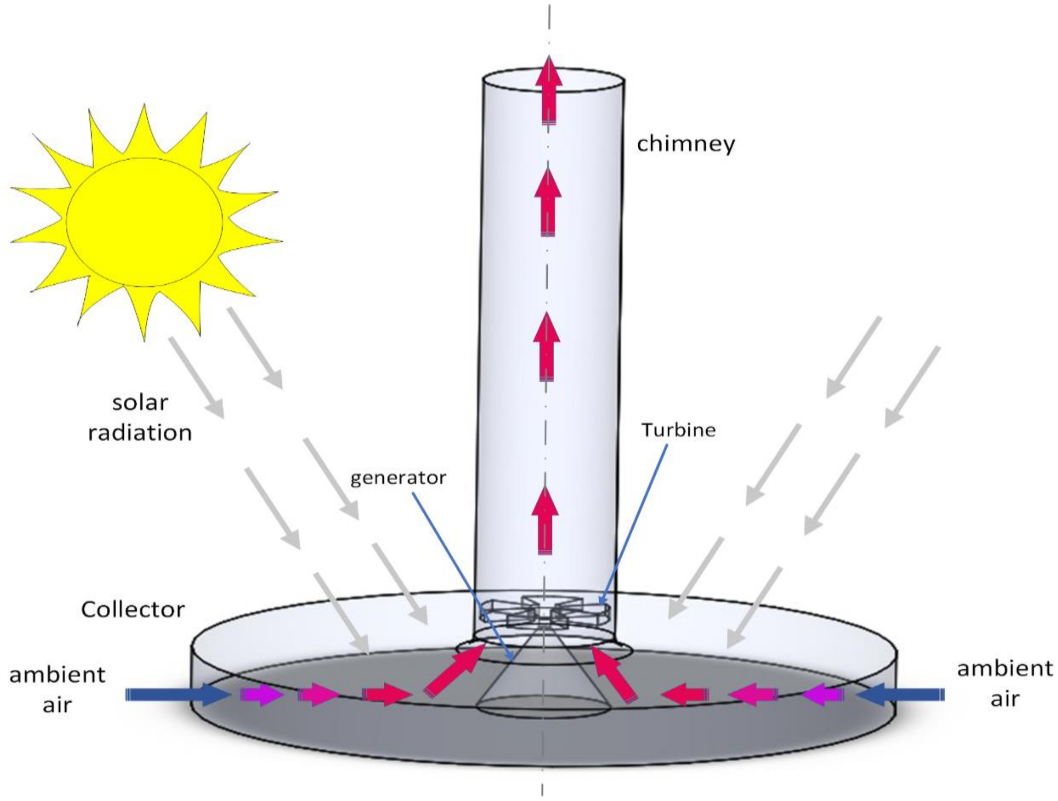


Figure 1. Schematic diagram of SCPP

Many studies proposed approaches of a solar chimney turbine and all of them aim to maximize the output power of SCPP system. Denantes and Bilgen [7] presented two counter vertical rotor turbines approached with/without inlet guide vanes and compared the performance of the presented configuration to a single turbine. Fluri and von Backström [8] presented many solar chimney turbine approaches; horizontal turbine, single vertical and counter vertical with/ without inlet guide vanes. Their conclusion is a vertical single turbine has the lowest efficiency but the widest efficiency range. Both of studies [7] and [8] used the mathematical model to demonstrate their results.

Lipnicki et al. [9] solved momentum, mass, and energy conservation equations of airflow inside a solar chimney system and used dimensionless numbers to describe the heat transfer phenomenon of a solar chimney system, then they compared the theoretical and experimental results. Pasumarthi and Sherif [10] also used the mathematical model to study effect of various parameters on the performance of SCPP. To validate theoretical these results, they carried out the experiment work and compared it against theoretical results [11]. Muhammed and Atrooshi [12] studied the collector and chimney area by modeling the heat and transport relations, they aimed to optimize dimensions for a solar chimney plant. Ismail et al. [13] improve both flow field and heat transfer characteristics of a collector of an SCPP using passive flow control, approaches have been numerically examined. Anther configuration to improve the heat transfer inside collector is presented by Fu [14] , who proposed a partial inclined and convergent collector design to enhance energy conversion efficiency. Nasraoui et al. [15] studied the effect of the chimney shape on the SCPP performance by testing different shapes numerically and experimentally.

Solar chimney system has a capability of cooperation the other renewable system for increasing profitable. Ahmed and Hussein [16] presented and tested the hybrid system of a solar chimney and PV panel to find the best configuration, which achieves the maximum available output power. Aurybi et al. [17] increased the output power of SCPP by adding thermal enhancing channels inside the collector. This proposed change increases the kinetic energy of the air, because of increasing the exit temperature of the collector especially at night time. Zuo et al. [18] proposed the integration solar chimney system and solar desalination technology and Zuo et al. [19] evaluated the performance of combination of a solar chimney power plant, seawater desalination and waste heat with/ without a wind supercharging.

In this study, I manufactured the solar chimney turbine by the 3D printing technology. The blade calculation was according to the Blade element theory (BET) as shown in ref [20] by author. Tests of the turbine are carried out on a wind tunnel of 1m diameter and 8 m length. I measured the electrical output power, pressure difference around the turbine and airflow rate to calculate dimensionless parameters.

2. Descriptions of the apparatus

Experimental works provide an accurate and realistic performance of the physical system; however, it is costly because of requiring more infrastructure. Therefore, we consider the experiment is an essential part of any research work. A wind tunnel is usually used for testing turbomachines because it saves the criteria of the operation condition during testing by strictly controlling inflow conditions. The blades and hub are a main construction of the conventional axial flow turbine; however, the blade shape has the essential influence of the capability to capture the energy from the air flow.

The rig of the experiment should allow for a detailed investigation of the turbine performance and satisfy the design objectives listed above. In this study, we chose the wind tunnel technique to test the solar chimney turbine, a wind tunnel is usually used for testing turbomachines because it saves the criteria of the operation condition during testing by strictly controlling inflow conditions. The blades and hub are a main construction of the conventional axial flow turbine; the blade consists of the aerofoils that interact with the hot air and convert the power in the air to mechanical power. The geometry and dimensions of the blades are determined by characteristics flow of SCPP to make it an optimum. 3D printing is used to manufacture blades of turbine prototype according to calculations of BET theory.

The tested prototype comprises the four-blade turbine rotor, which connects to the electrical generator that working as the load of the turbine. The hub is the part that transmits all the power and loads from the blades to the generator shaft. I designed the hub as two prats that makes it can change the angle of the blades, and easy to manufacture and assemble by 8 bolts. Figure 2. shows the prototype hub, which manufactured of polyethylene.

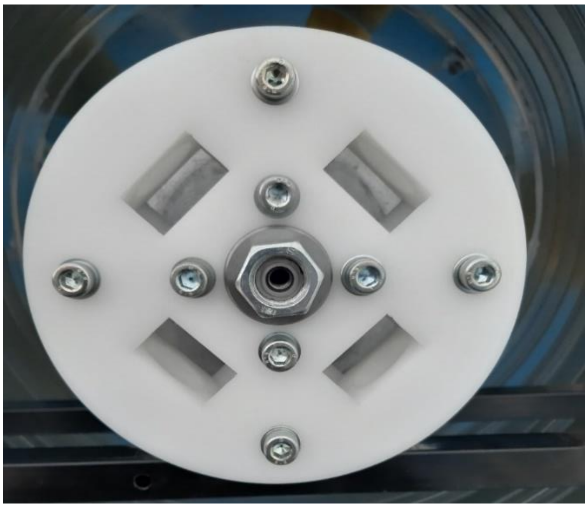


Figure 2. The hub of the tested turbine

The experiment is carried out in the energy laboratory, Hungarian University of Agriculture and Life Sciences (MATE) at Gödöllő campus. I used the wind tunnel, 8 m of length and 1 m of the square/circle cross-section, as shown Figure 3. Its first block from the inlet side has the laminar basket for damping the inference of surrounding. The draft fan connects with the suitable inverter, the inverter saves a proper control of the rotational speed of the fan, consequence, providing the control of the airflow velocity.

Figure 3. The wind tunnel at Hungarian University of Agriculture and Life Sciences (MATE) at Gödöllő campus

3. Measurement strategy

To evaluate the performance of the solar chimney turbine from the experimental rig, certain physical properties have to be measured, then, the dimensionless variables have to be determined from this measured quantity. The Physics quantity as:

- Airflow velocity, v_{in}.
- Pressure drops around turbine, $\Delta p_{tur,st}$.
- DC Voltage, V.
- DC Current, I.
- Outside Air temperature and humidity.
- Reference pressure.
- Rotational speed of the turbine.

Figure 4 shows the schematic and layout of the wind tunnel testing for the designed turbine. After fixation the rotor of the turbine on the generator shaft and the prob of the sensors as shown in Figure 4, the procedure of the solar chimney turbine will be carried out by following the next steps:

1- Turn on the fan on the low speed and check the sensors reading on the laptop screen.
2- Adjust the fan on the required speed and waiting for few minutes to achieve steady state operation.
3- Change excitation voltage of the generator
4- Start recording the data logger and manual reading (electric power, voltage, and current) for about 15 minutes
5- Stop the fan and prepare to the next reading
6- Repeat the above steps with a new speed

4. The sensors of the measurements

Many sensors were used in this work, all sensors connect to the data logger of ALMEMO 2590-9, which has 8 channels for sensors, and two channels for commination computer or other data logger. ALMEMO Control 5.20 software is used on the computer system to read the recorded value, then making it presentable. Figure 5 shows the location of the sensors inside the wind tunnel the more details about each sensor as following:

- *Anemometer*

One of the main parameters that affects the performance of the turbine is the inlet air velocity. FVAD 15-H series hot-wire anemometer instrument was used to measure the air velocity then the air mass flow can be calculated by multiplying with the cross-section area and the air outlet density. The measuring range is 0.3 to 40 m/s. The anemometer woks with ALMEMO 2590-9 Data logger. The accuracy is ±2% with mentioned working range. The air flow rate had been measured 2.5m from the inlet of the wind tunnel as shown in Figure 5.

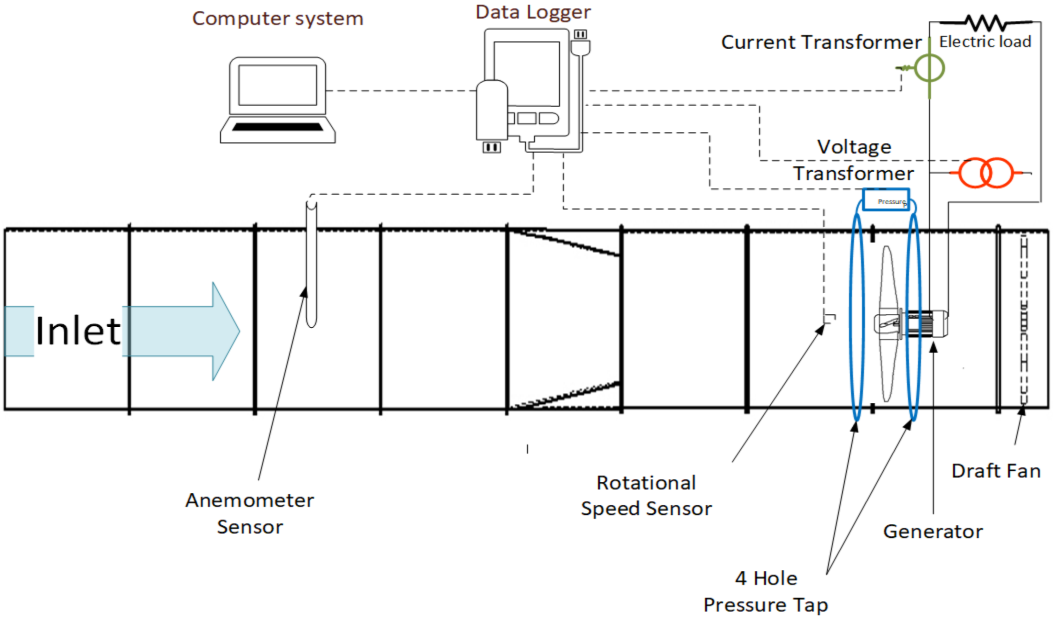


Figure 4. Schematic diagram of testing the turbine within wind tunnel

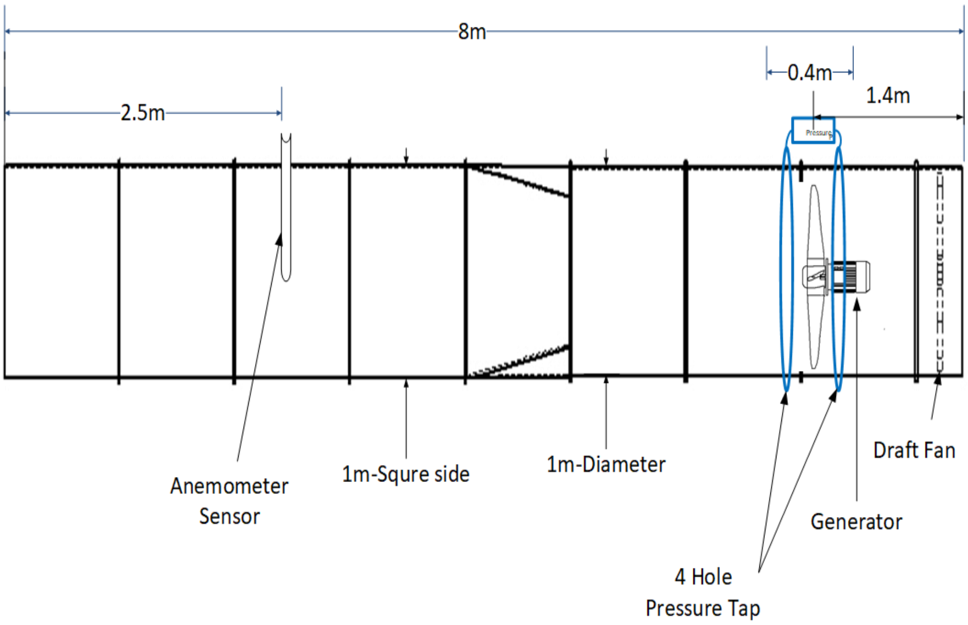


Figure 5. Locations of the sensors on the wind tunnel

- *Pressure gauge*

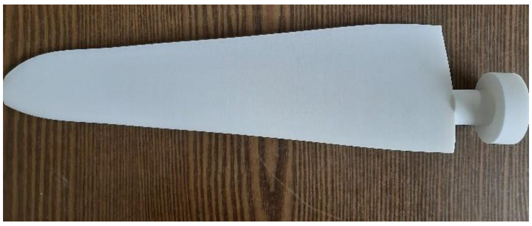
The effect of the turbine on the airflow reveals by the pressure drop of it, the pressure difference around the turbine indicates to us; the quantity of power that the turbine can absorb from the airflow. An FDA 602 S1K / S6K Differential pressure is used to measure the pressure drop around the turbine, it has Max. common mode pressure 700 mbar within -10 to +60 °C, 10 to 90% RH, and its dimension is 74 x 20 x 8.8 mm. Figure

6 shows the pressure sensor, which also can woks with ALMEMO 2590-9 Data logger and its Accuracy is ±0.5% of final value in range zero to positive final value.

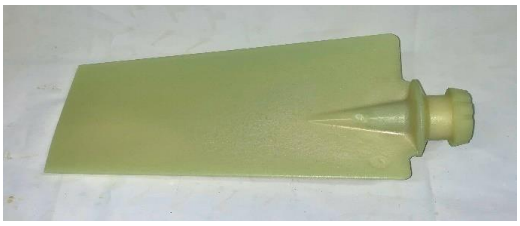
Figure 6. Differential pressure sensor

4. Results

Wind tunnel testing provides an accurate performance of the physics system, but they do it under the very strict operating conditions to ensure the stability of the system. This condition and stability assist in the systems investigation and going deeply in some point. I tested two turbines; the industrial fan rotor that was manufactured by MULTI WING and model of MWCZF2505041, and the second one is the turbine designed according to our calculation, which was manufactured by 3D printing technology. The geometry of the experimented elements is shown in Figure 7 as; Figure 7-a show the designed blade and Figure 7-b show the industrial one.



a. Designed blade



b. Industrial blade

Figure 7. Goemetery of the experimented blade

The electrical load of the turbine is the generator, changing the excitation to change the torque against turbine torque. Figure 8. shows the different excitation of the generator for the industrial turbine. The change of the excitation has a minor effect on the rotational speed of the turbine because the turbine works at the near its designed tip speed ratio. The generator construction puts its limit on the excitation power.

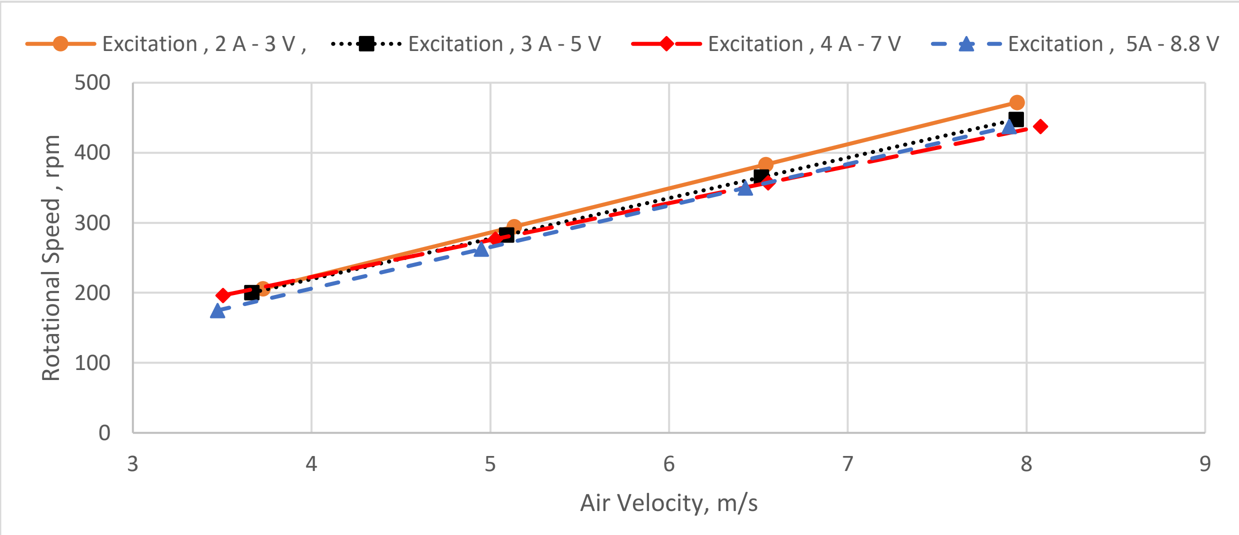


Figure 8. The rotational speed of the industrial turbine at the different excitation power

The generator shows the same behaviour on the designed turbine, as shows in Figure 9. The turbine has the higher rotational speed on the 8 m/s as design point while I calculated my design at 5.5 Tip speed ratio. The designed turbine achieved higher rotational speed than the industrial one at low air velocity (5-8 m/s), that give the designed turbine advantages to work at this range of air velocity.

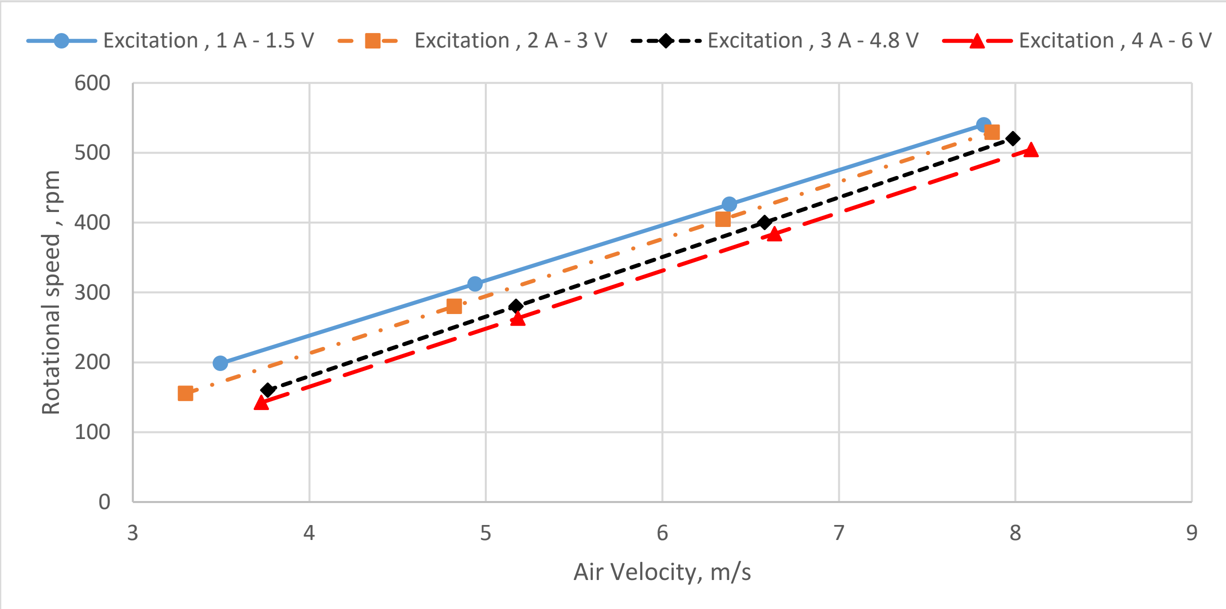


Figure 9. the rotational speed of the designed turbine at the different excitation power

Figure 10 shows the pressure drop by the turbine pressure drop has a dominant influence on performing the SCPP, indicates what energy is absorbed by the turbine at excitation of generator by 2 A - 3 V. The pressure drops increases with increasing the inlet velocity because more energy is available for the turbine by the airflow. Generally, the pressure drop of the designed turbine is higher than the industrial turbine by 1.5 times approximately at all points. The designed turbine achieved 65.08 Pa of the pressure drop, while the industrial turbine achieved 43.93 Pa at the inlet velocity of 15 m/s.

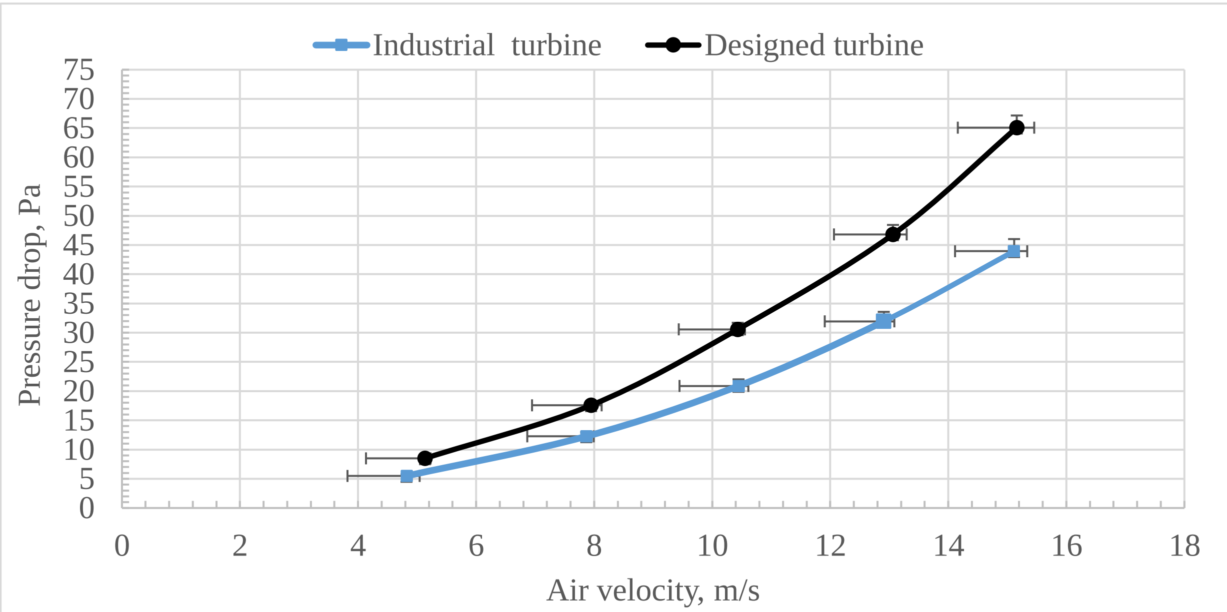


Figure 10. Pressure drop around the turbine

Output power is the major purpose of the system, the turbine produces power that is proportional to inlet fluid power. In the case of the shrouded turbine, fluid power is a combination of the kinetic energy of airflow and pressure energy. Figure 11. shows the power of the turbine according to the inlet velocity of the airflow at excitation of generator by 2 A - 3 V. The designed turbine achieved more power than the industrial one. The designed turbine comprises 4 blades, and the industrial turbine comprises 3 blades, the designed turbine produces 520 W, and the industrial turbine provides 380 at 15 m/s inlet velocity. Thus, the designed turbine produces 26.92 % higher than the industrial one as average increase on all points.

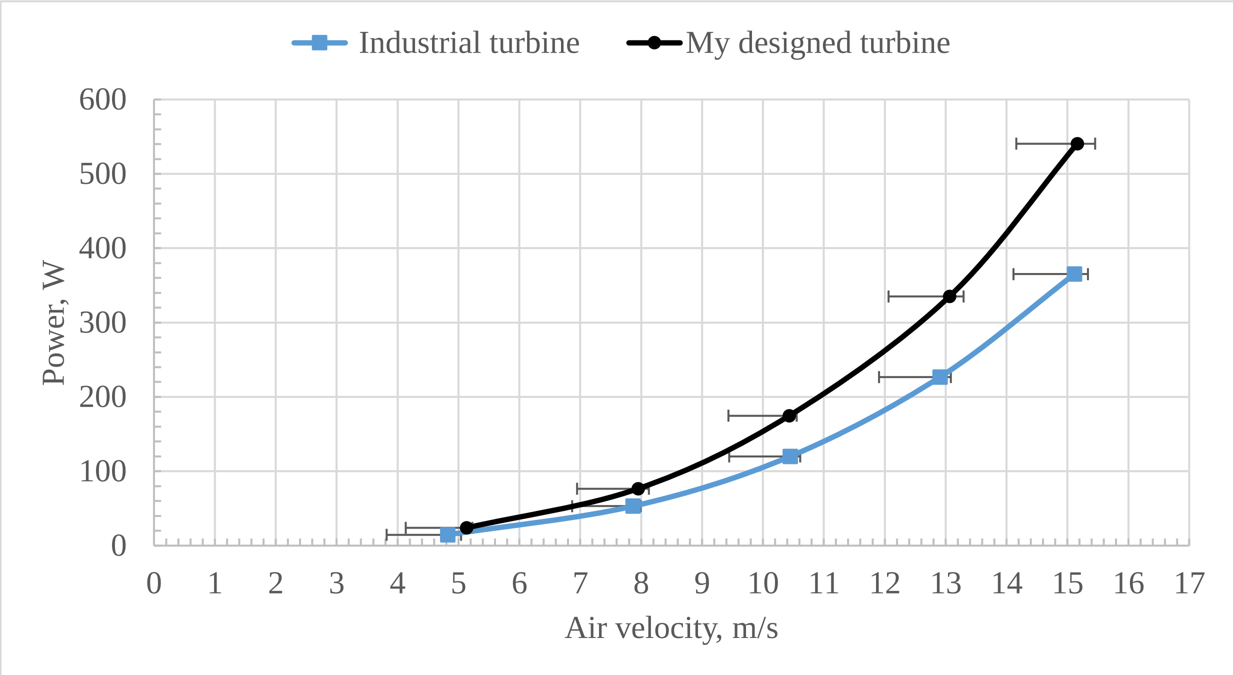


Figure 11. Power of the turbine vs. the inlet velocity

5. Conclusions

Wind tunnel testing provides an accurate performance of the physics system. The experiment is in the energy laboratory, Hungarian University of Agriculture and Life Sciences (MATE) at Gödöllő campus. I tested two turbines; an industrial fan rotor that was manufactured by MULTI WING and model of MWCZF2505041, and a turbine designed according to my calculations and manufactured by 3D printing technology. we measured the power, flow rate, rotational speed and pressure drop of the designed and industrial turbines within the wind tunnel, and the power coefficient of the turbines are calculated by measured values.

The turbine designed by me achieved more power than the industrial one. The designed turbine comprises 4 blades, and the industrial turbine comprises 3 blades. The turbine designed by me produced 520, and the industrial turbine provided 380 W at 15 m/s inlet velocity. Thus, my designed turbine produced near to 12% higher power than the industrial one on all points of measurement.

Power coefficient and tip speed ratio variables have to be determined from the measured quantity, as shown in Table 1.. Figure 12. shows the power coefficient that achieved according to tip speed ratio. The highest power coefficient of the designed turbine is 0.45 achieved at a 5 tip speed ratio, while it was designed at 5.5 tip speed ratio. The highest power coefficient of the industrial turbine is 0.32 achieved at a 3.3 tip speed ratio. The designed turbine achieved power coefficient 1.4 times (approximately) higher than the other turbine.

Table 1. Sample of the experimental data

My Designed turbine				
Inlet Velocity (m/s)	Rotational speed (rpm)	Outlet Power (W)	Power Coefficient	Tip Speed ratio
4.949637112	476.9230769	23.33086675	0.44540822	5.045144391
7.902899913	823.0769231	75.96867313	0.3563055	5.453214313
10.56070584	612.3076923	173.0338108	0.34009446	3.035815624
13.03536116	727.6923077	320.791605	0.33527504	2.922963135
15.38203959	878.4615385	536.8006359	0.34144336	2.990249657
16.66507328	1026.153846	767.3410202	0.38380812	3.224065615
Industrial turbine				
Inlet Velocity (m/s)	Rotational speed (rpm)	Outlet Power (W)	Power Coefficient	Tip speed ratio
5.170658438	280	17.64671834	0.29551112	2.835376943
7.984517832	520	54.18487745	0.24642198	3.409991299
10.45852021	735.3846154	122.2511203	0.24739422	3.681653585
12.74871903	916.9230769	219.740332	0.24550343	3.76586698
15.13228875	1123.076923	360.1664686	0.24062284	3.88600635

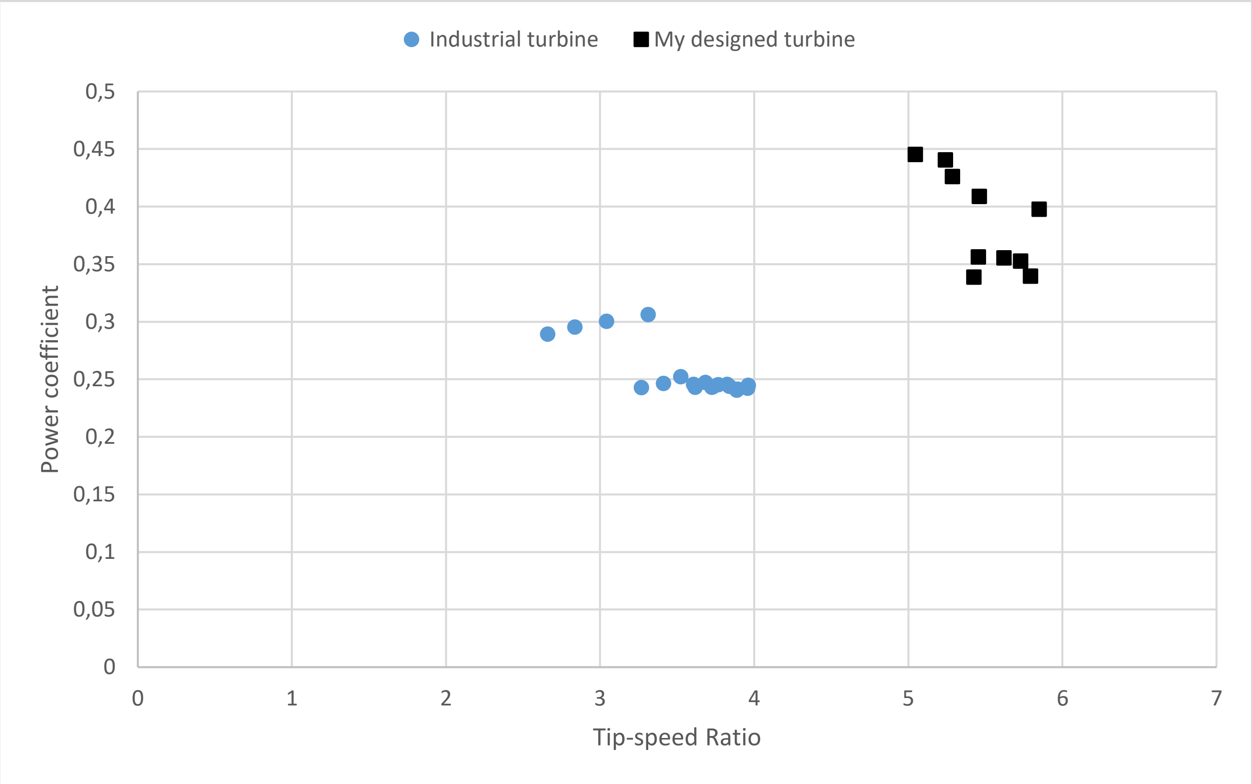


Figure 12. Power coefficient of the tested turbines

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