Design and Experimental Characterization of an Indoor-Scale Artificial Updraft Vortex Power Generator

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Abstract. An indoor-scale experimental model of artificial vortex power generator has been designed and tested. The model consists of four main components which are collector, tower, guide walls, and heating system. The collector and tower are constructed from poly-methyl methacrylate material. Both collector and tower are translucent allowing flow visualization experiments with laser and smoke to be performed for experimental characterization. The experimental model converts the supplied thermal energy into kinetic energy in form of updraft vortex airflow. Magnitude of the artificial updraft vortex is measured using a fan installed at the center of the tower. Rotational speed of the fan is measured by using a high-speed camera. The results show that the experimental model capable to rotate the fan up to 200 rpm.

1. Introduction
Developing renewable energy technologies is nowadays a key issue for sustainable environment and human living. The characteristic of renewable energy is that it often depends on natural condition. For example, a photovoltaic panel convert the light and energy of the sun into electricity. The power generated from this device is depends on the intensity of light. when the sky is scattered with clouds, the generated electrical power is reduced. Past efforts have been made to improve the efficiency of solar photovoltaics \[1 – 6\]. Nevertheless, intermittency and unpredictability of solar photovoltaics are still a major issue to be solved in commercial implementations.

Similar situation is observed in the wind turbine applications. The generated mechanical and electrical power are heavily depending on the natural wind velocity. Offshore and coastal area are often selected as the best location for the installation of wind turbines. Higher wind speeds are available in these areas compared to on land. As consequence, the number of offshore wind turbines is growing steadily in the last decade. Previous efforts have been made to optimize the wind energy utilization \[7 – 12\]. However, it also has similar drawbacks to solar photovoltaics where the resource is intermittent.

Different approach has been taken by other researchers to utilize both solar and wind energy. Solar updraft power generator is one of the renewable energy technologies that use both solar and wind energy to generate electrical power \[13\]. It consists of three main components namely collector, turbine, and tower. The solar updraft power generator converts the thermal energy from solar radiation into kinetic energy to be harvested by a wind turbine. It creates artificial updraft flow as a result of density differences of the air inside and outside the system. The characteristics of solar updraft power generator is that its efficiency is lower compare to solar photovoltaics and wind turbine. However, it
offers an effective and reliable ways to produce renewable energy since the heat from solar radiation can be stored for electricity production when sunlight is not available [14,15,16]. Furthermore, a modification of the solar updraft technology has also been reported to improve its total efficiency. Instead of creating artificial axisymmetric flow, an updraft vortex flow is created inside the system. Figure 1 shows the generated artificial updraft vortex by the experimental model developed by The Georgia Tech-led team [17]. The system uses a set of guide walls to force the buoyant, ground-heated air layer to rotate as it rises. The mechanism yield to a columnar vortex that can be anchored and which draws in additional hot air to sustain itself. It provides a new thermomechanical link between solar, wind, and electrical energy. Figure 2 show a formation of swirling wind from a modified solar updraft power generator model. This experimental model has been developed to produce artificial swirling wind for electrical power generation [18,19]. Series of guide walls is used in the system to form a rotational flow in the collector. These flows are rises at the collector outlet forming an updraft vortex or swirling wind with significant kinetic energy. These past works demonstrate the potential of harvesting artificial vortex flow (a tornado-like flow) for electrical power generation. The current work shares the same objective which is to design and test the artificial vortex power generator.

Figure 1. Generated artificial updraft vortex [17]
2. Experimental Setup

The experimental model in the current work consists of four main components; collector, tower, guide walls and heating system. These four parts are combined to form an indoor-scale experimental model capable in generating artificial updraft vortex flow. The discussion begins with the design of heating system.

2.1. Design of Heating System

The heating system is designed to replace the radiation heating from solar radiation. An electrical heating element was used to generate heat and installed beneath a $1 \times 1 \text{ m}$ aluminium plate. The plate has 10 mm of thickness and act as heat absorber. The heating element was buried inside isolator material in order to assure the heat flows in axial direction only. It is made from nichrome materials and has good performance under high temperature. The material also has a reasonable resistance and produces a consistent amount of heat when it connects to electricity. Figure 3 shows the design and arrangement of the heating system.

Figure 2. Formation of artificial swirling wind [19]
Figure 3. Design and arrangement of heating system (top and side views).

2.2. Design of Collector Profile and Tower
The collector profile has a tapered design. The collector is suspended 75 mm at the outer region and 50 mm at the inner region. The inner region refers to the center of the collector where it has the highest updraft velocity. The collector and the tower are transparent and made from poly-methyl methacrylate material. The tower has 1500 mm of height and 50 mm of diameter. The tower and the collector are combined to form a basic (without guide walls) experimental model as shown in Figure 4.

Figure 4. Design and arrangement of collector and tower

2.3. Design of Guide Walls
The guide walls are designed to channel the heated airflow into the tower inlet. The swirl airflow in the collector outlet transform into a columnar updraft vortex in the tower inlet. The guide walls are made from aluminium plate with 0.8 mm of thickness and has a tapered profile. Outer and inner height of the guide walls are 75 mm and 50 mm respectively. The tapered design of guide walls follows the
collector profile where its outer and inner height have different values. Figure 5 shows the design and arrangement of guide walls on top of the heating system.

![Design and arrangement of guide walls](image)

**Figure 5.** Design and arrangement of guide walls

### 2.4. Measurement Procedure

Two types of measurement were performed in the current study. The first measurement is to obtain the characteristics of updraft velocity and temperature at the center of collector for the basic configuration (without guide walls). Two thermo-anemometers were used in the measurement process. The first sensor is placed at the top of the tower. The second sensor is installed at the center of the collector where this region is recognised to have the highest updraft velocity. In addition, one thermocouple was also installed on top of the aluminium plate to measure the plate’s temperature. The measurement period was selected to be 60 min with sampling rate for both velocity and temperature was set to 60 sec. Hence, the digital reading produces 60 data points at the end of measurement process. Arrangement and installation of the sensors is presented in Figure 6.

![Location of sensors](image)

**Figure 6.** Location of sensors
The second measurement is for flow visualization. In this process, smoke was used to visualize the airflow inside the collector. The airflow is illuminated by laser sheet and results were captured by a high-speed camera. In order to quantify the strength of the updraft vortex, a small fan was installed at the center of collector. The rotational speed of the fan is measured by counting the time taken to complete one full rotation and the result is presented in rotation per minute (rpm).

3. Measurement Results

3.1. Updraft Velocity and Temperature

Updraft velocity and temperature are defined as the airflow velocity and temperature at the center of collector. These physical parameters were measured for basic configuration (without guide walls) to evaluate the performance and the aerothermal characteristics of the experimental model. Figure 7 present the measured updraft velocity and temperature at both top and bottom of the tower (center of collector). It can be observed that, the increase of temperature results in increase of velocity. The updraft velocity at the bottom of the tower exhibits a higher magnitude compare to the top of the tower. This is because the updraft flow loses its kinetic and thermal energy during its travel along the tower, indicates by a lower velocity and temperature.

The updraft velocity at the bottom of the tower was able to reach up to 3 m/s while the updraft temperature peak at 53 °C. About 61.6 % reduction of updraft velocity is calculated between the peak
value at the bottom and at top of the tower, while 23.1% is calculated for reduction of updraft temperature. Furthermore, the measurement result of updraft velocity at the bottom of the tower shows a scatter pattern after 20 min of measurement time. Significant heat losses at the edge of collector was responsible for the pattern. It can be inferred that the airflow towards the tower are affected by the backflow at the edge of collector due to heat loss.

3.2. Artificial Updraft Vortex
The guide walls are installed in a basic configuration of the experimental model to produce updraft vortex flow. Initial swirl flow is start to build up in the collector upon reaching the tower inlet due to installation of guide walls. The swirl flow is reached the inlet forming a columnar vortex along the tower center line. The vortex can be sustained as long as there is heat supplied to the system [20]. Therefore, the magnitude of the artificial vortex can be controlled through the heat given to the system. The artificial updraft vortex mimics the real-life tornadoes. However, the tornadoes are naturally formed and difficult to control, sustain, and harvest for electrical power. Figure 8 shows the flow visualization result on the formation of artificial updraft vortex inside the tower. Three regions were identified in this Figure, they are boundary layer region near the wall of the tower, low-pressure region at the core of the vortex, and high velocity region in between the boundary layer and low-pressure region.

Figure 8. Formation of updraft vortex inside the tower

The strength of the updraft vortex was quantified by using a small fan placed at the center of the collector. The rotational speed of the fan was measured by counting the time taken to complete one full rotation using a high-speed camera. Figure 9 shows the process to count the fan’s rotation.
### Figure 9. Process to count the fan’s RPM

### 4. Conclusion

An indoor-scale artificial updraft vortex power generator was designed and tested. It consists of four main components: collector, tower, guide walls, and heating system. Measurement results showed that the updraft velocity was able to reach up to 3 m/s for basic configuration. Addition of guide walls produce initial swirl airflow in the collector and columnar vortex along the tower center line. The strength of the generated vortex was measured by using the fan rotational speed in RPM. It was observed that the experimental model was able to rotate the fan up to 200 rpm. The current

| Position    | Time [s] | RPM  |
|-------------|----------|------|
| Initial     | 0.030    | -    |
| ¼ rotation  | 0.105    | 200  |
| ½ rotation  | 0.181    | 197.37|
| ¾ rotation  | 0.258    | 194.81|
| 1 rotation  | 0.334    | 197.37|
| Average     |          | 197.38|
experimental model and measurement results demonstrates the potential of harvesting a tornado-like flow for electrical power generation.

5. References
[1] R. Nadda, A. Kumar, and R. Maithani, “Efficiency improvement of solar photovoltaic/solar air collectors by using impingement jets: A review,” *Renew. Sustain. Energy Rev.*, vol. 93, pp. 331–353, 2018.
[2] A. Benlekhdim, A. Cheknane, L. Sfaxi, and H. S. Hilal, “Efficiency improvement of single-junction InGaP solar cells by advanced photovoltaic device modeling,” *Optik (Stuttg).*, vol. 163, pp. 8–15, 2018.
[3] J. Singh, A. Kumar, A. Jaiswal, S. Suman, and R. P. Jaiswal, “Luminescent down-shifting natural dyes to enhance photovoltaic efficiency of multicrystalline silicon solar module,” *Sol. Energy*, vol. 206, pp. 353–364, 2020.
[4] A. K. Suresh, S. Khurana, G. Nandan, G. Dwivedi, and S. Kumar, “Role on nanofluids in cooling solar photovoltaic cell to enhance overall efficiency,” *Mater. Today Proc.*, vol. 5, no. 9, pp. 20614–20620, 2018.
[5] T. N. Ngoc et al., “A hierarchical architecture for increasing efficiency of large photovoltaic plants under non-homogeneous solar irradiation,” *Sol. Energy*, vol. 188, pp. 1306–1319, 2019.
[6] K. Yadav, A. Kumar, O. S. Sastry, and R. Wandhare, “Solar photovoltaics pumps operating head selection for the optimum efficiency,” *Renew. Energy*, vol. 134, pp. 169–177, 2019.
[7] D. Song et al., “Optimal design of wind turbines on high-altitude sites based on improved Yin-Yang pair optimization,” *Energy*, vol. 193, p. 116794, 2020.
[8] J. M. Hegseth, E. E. Bachynski, and J. R. R. A. Martins, “Integrated design optimization of spar floating wind turbines,” *Mar. Struct.*, vol. 72, p. 102771, 2020.
[9] S. Pookpunt and W. Ongsakul, “Optimal placement of wind turbines within wind farm using binary particle swarm optimization with time-varying acceleration coefficients,” *Renew. Energy*, vol. 55, pp. 266–276, 2013.
[10] K. Qasemi and L. N. Azadani, “Optimization of the power output of a vertical axis wind turbine augmented with a flat plate deflector,” *Energy*, vol. 202, p. 117745, 2020.
[11] A. Saleem and M. H. Kim, “Aerodynamic performance optimization of an airfoil-based airborne wind turbine using genetic algorithm,” *Energy*, vol. 203, p. 117841, 2020.
[12] S. Acarer, Ç. Uyulan, and Z. H. Karadeniz, “Optimization of radial inflow wind turbines for urban wind energy harvesting,” *Energy*, vol. 202, 2020.
[13] P. Guo, T. Li, B. Xu, X. Xü, and J. Li, “Questions and current understanding about solar chimney power plant: A review,” *Energy Convers. Manag.*, vol. 182, pp. 21–33, 2019.
[14] Y. Xu and X. Zhou, “On-line power management for grid-connected solar chimney power plants with various heat storages,” *Energy Convers. Manag.*, vol. 187, pp. 167–175, 2019.
[15] R. Balijepalli, V. P. Chandramohan, and K. Kirankumar, “Performance parameter evaluation, materials selection, solar radiation with energy losses, energy storage and turbine design procedure for a pilot scale solar updraft tower,” *Energy Convers. Manag.*, vol. 150, pp. 451–462, 2017.
[16] A. A. Sedighi, Z. Deldoost, and B. M. Karambasti, “Effect of thermal energy storage layer porosity on performance of solar chimney power plant considering turbine pressure drop,” *Energy*, vol. 194, p. 116859, 2020.
[17] M. W. Simpson and A. Glezer, “Buoyancy-induced, columnar vortices,” *J. Fluid Mech.*, vol. 804, pp. 712–748, 2016.
[18] Y. He et al., “Feasibility of a new helical blade structure for a PV integrated wind turbine in a heat-driven swirling wind field,” *Energy*, vol. 185, pp. 585–598, 2019.
[19] M. Zhang et al., “From Dust Devil to Sustainable Swirling Wind Energy,” *Sci. Rep.*, vol. 5, pp. 1–5, 2015.
[20] A. Mohiuddin and E. Uzgoren, “Computational analysis of a solar energy induced vortex generator,” *Appl. Therm. Eng.*, vol. 98, pp. 1036–1043, 2016.