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EXPERIMENTAL OPTIMIZATION OF HEAT-INDUCED CONVECTIVE FLOWS FOR UPDRAFT VELOCITY IMPROVEMENT IN TORNADO-TYPE WIND POWER GENERATOR

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A R T I C L E I N F O

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Renewable energy
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Tornado-type power generator

A B S T R A C T

A fundamental experiment with purpose to find the optimum design and configuration of a tornado-type wind power generator has been conducted. In this work, a series of guide walls was installed inside the collector of a conventional Solar Updraft Power Generator (SUPG) with purpose to concentrate the airflow. The updraft velocity are measured and compared for two cases namely; with and without guide walls. Experimental result showed that the updraft velocity for the case with guide walls is higher compare to those without guide walls. About 18% and 64% improvement of updraft velocity and mechanical power were attained respectively.

1. Introduction

The global energy is primarily supplied from fossil fuels and the fact that fossil fuels are not a sustainable resource along with demand for this finite resource is only increasing add another issue of global energy. Even if the global fossil fuels are not running out soon, it might be the case that one country has run out of fossil fuels and this country might have to depend on another country's resources in the future. So the energy security supply is also one of the reasons why it is necessary to look into a variety of renewable resources and shift the global energy supply from finite to a sustainable resource. Solar updraft power generator or SUPG is one of the sustainable power production facilities which utilize solar radiation to increase the temperature of working fluid under the solar collector so that it is less dense than the ambient air at the top of solar tower, inducing a buoyancy force in form of updraft flow that simultaneously entrains the working fluid. The desired kinetic energy from the updraft flow is then harvested into electrical energy by installing one wind turbine at the bottom of the solar tower or series of wind turbine in circumferential manner at the center of collector.

2. The Manzanares Project

A prototype of the solar updraft power generator was constructed and operated since June 7th, 1982 on a site in Manzanares provided by the Spanish utility Union Electrica Fenosa (Haaf et al. 1983). The prototype has 194.6 m of tower height with diameter of 10.16 m, and the collector has 244 m mean diameter covered by different types of film-PVC with thickness of 0.1 mm. The collector canopy was installed 2 m from the ground level. A 4-blade vertical-axis wind turbine was placed at a height of 9 m from the ground level and has 5 m of blade radius. With this configuration, the prototype was able to produce 50 kW of peak power (Haaf, 1984).

Figure 1: A picture of the Manzanares SUPG in Spain

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3. Recent Development in SUPG

Despite the active development on the conventional design and configuration of solar updraft power generator, there is also a number of active research groups who concentrates on finding an innovative method in utilizing the solar-induced wind energy concept and designing a new configuration of solar updraft power generator. For example: the concept of generating the atmospheric vortex which has been realized into a vortex engine power generator by Michaud (2007). The design of this engine can be seen in Figure 2 (top) which shows the formation of an updraft vortex as a result of channeling the airflow by series of guide walls.

Another power generator which aims to produce an updraft vortex has also been investigated by a research group in Georgia Institute of Technology, USA (Simpson et al. 2013). The prototype can be seen in Figure 2 (bottom). The electrical power is generated from “anchored” columnar vortices that can be controllably formed in areas with high surface heating rates. These vortices entrain the ground-heated air layer where the solar heating process from solar radiation is occurred and subsequently converting the (gravitational) potential energy into kinetic energy. The main difference between this power generator (the solar vortex) and the vortex engine is: the solar vortex deliberately triggered and anchored columnar vortices in order to sustain an updraft vortex.

Figure 2: Atmospheric vortex engine (top) and the solar vortex (bottom)

4. Design of Experiment

The experiment designed in this work has the purpose to find the optimum design and configuration of a lab-scale SUPG. The experiments were conducted by varying the geometry (collector height, tower diameter and tower height) of a lab-scale SUPG. The optimum design was then used to be further investigated in the developments of axial updraft vortex flow.

4.1. Experimental Setup

The schematic drawing of experimental setup is presented in Figure3.

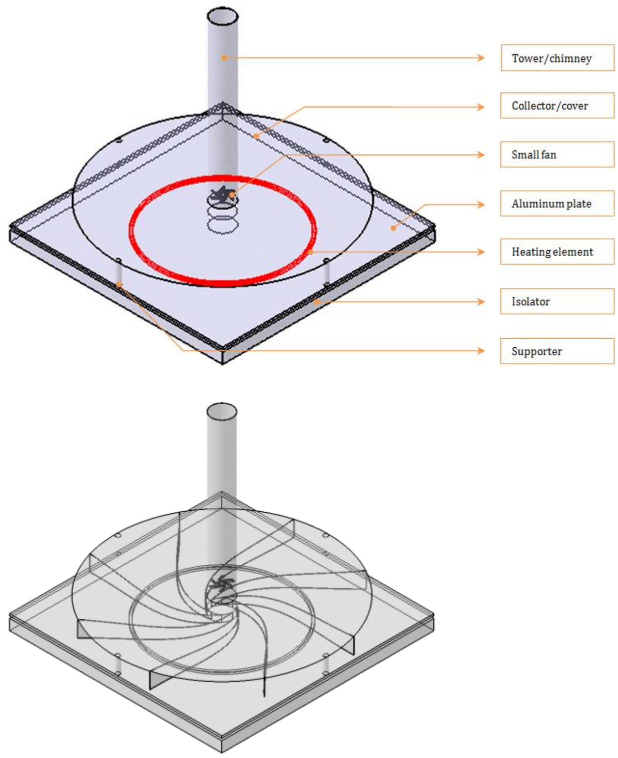

Figure 3: Schematic drawing of a lab-scale SUPG.

The experimental apparatus includes heating system, transparent collector/cover and tower, heat absorber, and series of guide walls. Heating system consists of one electric thermal element made by nichrome materials and it is circularly buried inside an isolator materials. In order to control the direction of heat flux, a gap of 10 mm opening is provided. The heats from this heating element are then convected and absorbed by a 1m × 1m aluminum plate with 10 mm thickness. The material for collector and tower is polymethyl methacrylate. The purpose to have a transparent collector/cover in this experiment is to allow visual inspection of the airflow inside the collector when flow visualization experiment is conducted.

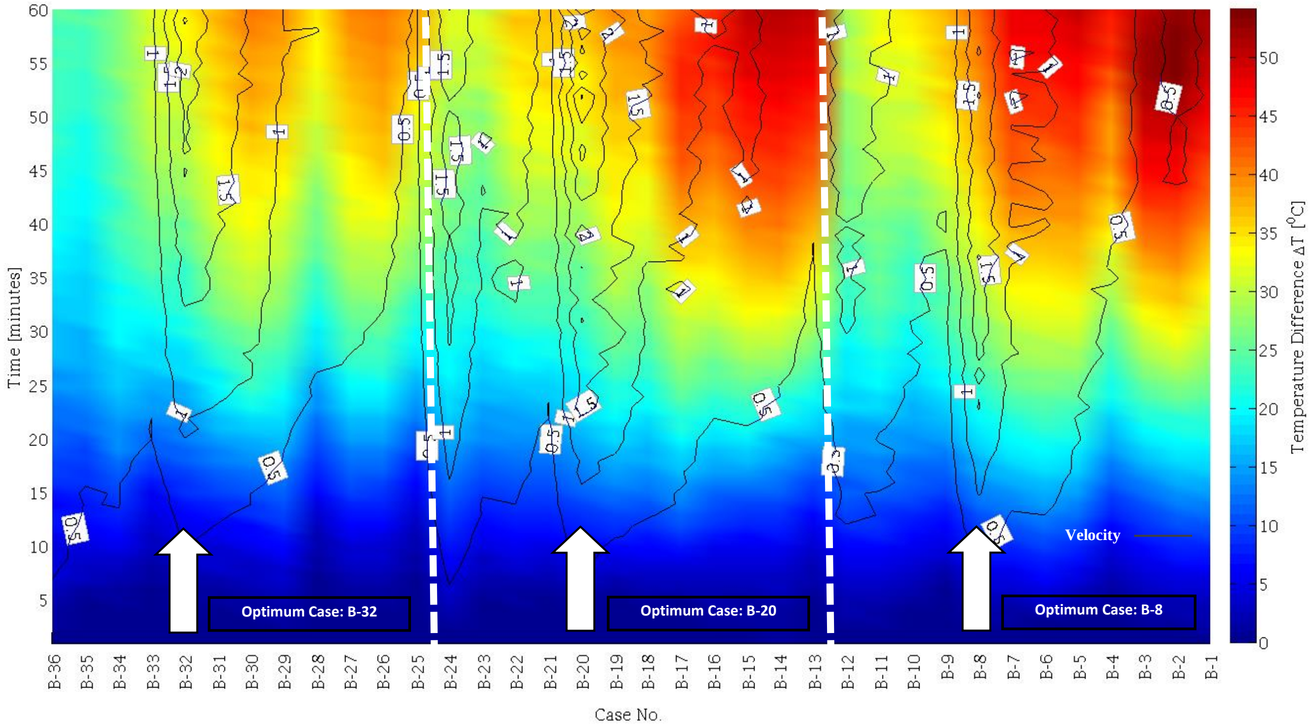

Figure 4: Temporal-spatial chart showing the evolution of updraft temperature and velocity for each experiment case.

4.2. Measurement Procedure

As mentioned in Hafizh et al. (2012):

Step 1) Select a collector type, tower diameter, and tower height and combines them to construct one configuration of a lab-scale solar updraft power generator.
Step 2) Setup a digital thermocouple at the center of aluminum plate to measure the temperature of plate and install two digital thermo-anemometers at the bottom and top part of the tower.
Step 3) Connect the thermo-anemometers with computer so that temperatures and velocities data can be stored digitally. After that, set the temperature sampling time for 5 seconds and velocity sampling time for 60 seconds. Also, set measurement time for 60 minutes with 1 minute data sampling.
Step 4) Turn on the electric heating element and immediately start the measurement. Velocity is automatically sampled by the sensor, but temperature must be manually sampled for every 1 minute by pressing the “store” button in the sensor device. In addition, temperature of plate must also be manually recorded for every 1 minute.
Step 5) after 60 minutes of measurement, turn off the electric heating element. Save temperatures and velocities data from the thermo-anemometer sensors.
Step 6) Repeat the procedures for another configuration of lab-scale solar updraft power generator.

For the case with guide walls, it is impractical to measure the absolute velocity of such complex flow since the streamline pattern of this flow will also change with the temperature. An indirect method to measure the absolute velocity is proposed by installing a small fan at the bottom of tower. Rotations of this fan were counted via high-speed camera as in Figure5.

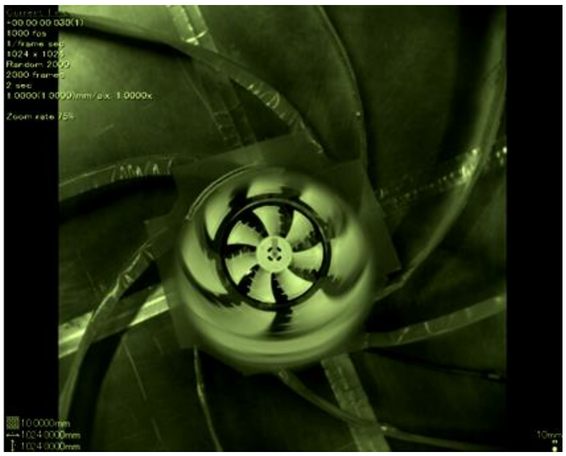

Figure 5: Snapshot picture from high-speed camera showing rotation of small fan inside the tower.

5. Experimental Results

5.1. Case1: Without Guide Walls

Experimental result for the case without guide walls is presented in Figure 4. It provides the information regarding the best design and configuration in term of utilizing thermal energy given to the system (indicated by the temperature difference) to be converted into kinetic energy (indicated by the updraft velocity).

The results are divided into three groups separated by white dashed line. One group represents the same collector height with various tower diameters and tower heights. The red color in this chart indicates a high temperature region. For example case numbers B-1 to B-4. These cases exhibit a high temperature region but the updraft velocity (contour line) remains low. Hence, this configuration is considered as the worst combination. The best combinations are observed for the case number B-8, B-20, and B-32 because these cases successfully utilize the heat given to the system to be converted into high updraft velocity.

The updraft velocity and temperature are the measured physical parameters. They were measured at the bottom and at the top of the tower. Nevertheless, the bottom part is the most important part since the turbine will be installed in this region. Thus, the updraft velocity and temperature for each optimum cases, which have been selected based on Figure4, are presented. These figures are depicted in Figures 6 to 8.

From these three optimum configurations, case no. B-20 is selected as the best design since its produce the highest updraft velocity among other cases. Higher updraft velocity is desirable since it will be used to rotate the wind turbine.

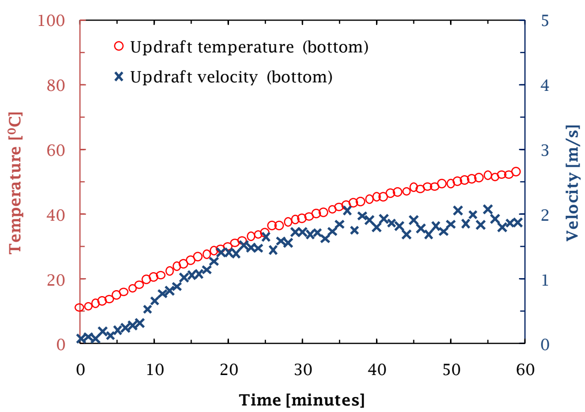

Figure 6: Updraft temperature and velocity for case no. B-8.

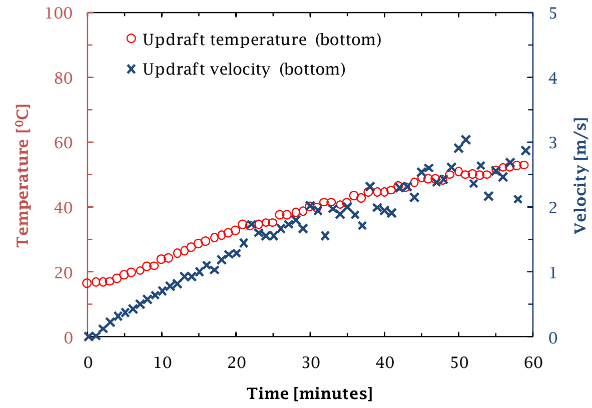

Figure 7: Updraft temperature and velocity for case no. B-20.

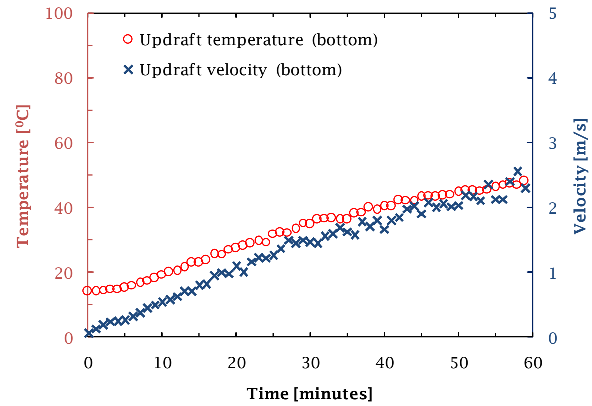

Figure 8: Updraft temperature and velocity for case no. B-32.

5.2. Case2: With Guide Walls

The experiment is attempted to compare the magnitude of updraft velocity for two cases namely; without guide walls configuration and with curved guide walls configuration. An alternative method to measure the magnitude of the updraft flow for both cases is proposed by placing a small fan at the bottom of the tower. This fan will rotate due to the oncoming updraft axial or vortex flow.

The rotation of fan was tracked by a high-speed camera which has capability of taking the picture up to 1000 frame per second. So the small fan was marked on its surface and the time taken for this marked to finish one rotation is followed and recorded. The results are presented in Figure9. Experiment was conducted for three configurations i.e. without guide walls, 4 curved guide walls, and 8 curved guide walls. Rotations of small fan for each case are recorded for three different absorber/plate temperatures (50, 60, and 70 ^{0}C).

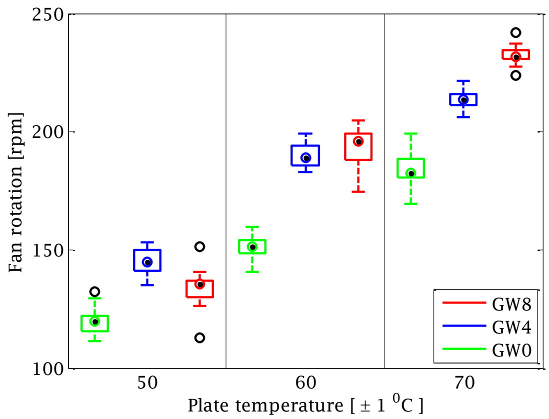

Figure 9: Graphical results of counting the fan rotation for three different cases.

5.3. Dynamic Similarity Analysis

In the current work, the geometric similarity is not satisfied since the geometry of lab-scale SUPG has been designed with purpose to find the optimum design by adjusting each geometrical parameter instead of testing the geometry scale down of the Manzanares SUPG. Although the geometry of lab-scale SUPG is not similar with the Manzanares SUPG, the similarity analysis can be conducted through dynamic similarity by recognizing the dominant parameters in the SUPG system.

Two forces are dominant and act as the driving force in the SUPG system. They are inertia and buoyancy forces. These two forces can be combined into one dimensional parameter which is Froude number; representing the ratio of inertia and buoyancy forces.

By comparing the Froude number of lab-scale SUPG with the Manzanares SUPG, increasing or decreasing of updraft velocity can be accessed. This is also directly related to the improvement of the total efficiency of SUPG system. Comparative study through similarity analysis via Froude number (Fr) is then proposed.

The Froude number from the Manzanares SUPG is calculated for ΔT=20 K and for the same amount of temperature difference, the Froude number from the lab-scale SUPG is also computed from numerical simulation with flat collector configuration. The same Froude number means a similar flow in the solar tower of two different sizes and their corresponding buoyant flows regardless the shape of the solar collector. Mathematically Froude number is expressed as:

$$Fr(\Delta T) = \frac{{u_z}^2(\Delta T)}{g h_{tow}} \frac{\rho_a(\Delta T)}{\rho_{a_\infty} - \rho_a(\Delta T)} \qquad (1)$$

Table 1: Froude number calculation

	Manzanares (Full scale)	Optimum Configuration (Experiment)	Improvement
ΔT	20	20	
Fr(ΔT)	1.73	2.5	
Updraft Velocity	15 m/s	17.7 m/s	18 %
Mechanical Power	47.26 kW	77.65 kW	64 %

The updraft velocity of Manzanares SUPG at ΔT=20 K is around 15 m/s with height of tower almost reaches 200 m. Therefore, the Froude number is obtained as 1.73. For the same amount of temperature difference, the Froude number of optimum configuration obtained from the experiment on a lab-scale SUPG is 2.50. The results are summarized in Table 1. It is clear that Froude number from the current experiment is higher than the Manzanares SUPG for the same amount of input indicated by the same condition of temperature difference. About 18% and 64% improvement of updraft velocity and mechanical power were obtained respectively.

6. Conclusions

Experimental optimization of a conventional SUPG was performed. One optimum configuration was selected to equip with guide walls in order to produce a rotating updraft flow. It was found that the rotating flow exhibit a higher magnitude of updraft velocity compared to the conventional axial updraft flow. Significant improvement of updraft velocity and mechanical power were attained about 18% and 64%respectively.

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