A Design for Increasing Power Using a Solar Tower Unit

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Abstract—In this work, power generation enhancement for a 2.00 meter height Hexagonal base solar chimney with a 6 double faced trapezium sides is introduced. Amount of energy acquired to rotate the generating part of the solar tower (Direct current fan on the exit) depends on the air flow which will increase with the temperature rise that is affected by the solar heat up of the double faced sides. Analysis and comparison based on taking different temperature readings in 3 cases for the stagnant fluid filling the gap of the double faced solar tower sides (air, vacuum and helium) to see the best case where the highest air temperature is reached and consequently having the highest generated power.

In addition to that, a Savonius air turbine is to be fitted on the top of the tower to get more power from the unit in dark time using the wind energy which is a continuous source not relying on solar energy.

Commercial power generation is not expected to be acquired from this model as it is made for the purpose of analysis that would provide useful conclusion that can be used in enhancement of the commercial model performance.

Keywords—Solar chimney tower, Direct current generator, Savonius turbine with Direct current generator, Temperature rise analysis, Savonius wind turbine generated power, Daily temperature variance and daily wind speed variance.

I. INTRODUCTION

Solar power generation is now considered as one of the most growing and desired kind of energy specially with the growing demand on electrical power for day to day activities that coincides with less power resources specially for fossil fuels that is also creating many issues for the environment and the big need for shifting round to the renewable energy resources (e.g. solar, wind, water, sea waves,..., etc..) which is more cheaper and effectively clean.

One of the most common renewable energy types is the solar energy with different power generation ways as follows:

1) Photovoltaic solar system, where light is converted into electricity using semiconducting materials that exhibit the photovoltaic effect.

Despite of being clean and cheap kind of energy but the fact that power output is dependent on direct sunlight is a disadvantage that would be overcome by continuous tracking system.

2) Thermal solar system, where different technologies are used to harnessing solar energy to generate thermal or electrical energy.

The present study considers the second type through focusing on power enhancement for one of the thermal power types which is the solar power chimney generator.
The commercial model of the solar power chimney is always around 100 meters height or more and usually constructed in agriculture areas to get use of greenhouse effect and sometimes on frozen land areas to get use of high sun ray reflection in such environments.

In previous work (paper ID: ICEST 2015), Basil Abdel Megied studied the effect of trapping air in 6 double face windows making up a 2 meters height solar tower model. The double face window has one aluminum face for the inner side and transparent glass face towards the ambient. This creates a greenhouse effect in the gap between the two faces that trapped heat energy inside and adding more energy to the air inside the solar tower bore represented in a 7 deg C temperature difference between the inlet air temperature (ambient) and the exit air temperature at the top of the tower that theoretically would result in more air bouncy due to density different and in turn more air flow with extra electrical power that can be obtained by rotating a direct current generator on a top exit of a solar chimney.

In the present study, similar tower was built by using 2 mm glass sheet for outer surface and 1 mm thickness aluminum sheet for inner surface, each double wall side is well isolated in order to see the effect on temperature rise in case of helium, air and vacuum filling the double wall gap, hence decision can be taken for the best filling fluid or vacuum media that would generate highest temperature.
For every case, air, helium or vacuum will be isolated in between the double face window with glass sheet outer face to absorb and trap solar energy to heat up the inner aluminum face. (Greenhouse effect)

In parallel to this process and to enhance the tower power generation, a wind turbine (Savonius type) is fitted to the top of the tower (far enough from the air generator exit) in order to obtain more power especially in dark time where no radiation exists. Such generated power will be obtained on a direct current motor.

For the purposes of enhancement measurements study, both sub units will be treated and studied individually by the mean of measuring sensors (J-type thermocouple for Temperature readings), interface (Digital/Analogue converter Siemens type) and desktop computer (Dell 3400).

Trapped solar energy in the window gap will transfer through stagnant air, helium or vacuum which will be better than only having solar energy absorbed by the black aluminum surface which will enhance the flowing air heating process and add more energy to it that will in turn gives more power to the air turbine on the top of the solar tower.

**Figure 3.** (a) Experimental tower for current study with Savonius turbine on top of it and (b) Computer and interface unit setup.

**II. EXPERIMENTAL SETUP AND METHODOLOGY**

1. DESIGN OF THE EXPERIMENT

   I. Heat transfer through every wall

   Heat radiation from sun is absorbed by glass after reflecting a portion of radiation waves continuing passing to the aluminum black sheet with most of it absorbed and some reflected that is in turn heats up the air flowing up to the generator, meanwhile some heat escapes out to the Ambient through the stagnated fluid and glass by conduction.
In addition and to enhance the unit efficiency (especially during sun radiation absence) a Savonius wind turbine was fitted to the top of the solar tower.

III. EXPERIMENTAL SETUP

A. Heating up Air Flow using Stagnated Air in wall gap.
Using air as stagnant fluid was the previous work done and applying this step is to validate the previous work and create a comparison with the next two initiatives (using helium & vacuum). Despite of the fact that having air as stagnated fluid in the wall gap enhanced the heating up when compared to the case with Aluminum sheet only but it is expected to have less heating up when compared to vacuum due to heat loss to the ambient through conduction.
B. Heating up air flow with helium in wall gap.
When compared to air, helium has higher thermal conductivity and this could only be an advantage if helium temperature is higher than aluminum sheet temperature otherwise heat loss via conduction through stagnant helium and glass will occur.

C. Heating up air flow using vacuum in wall gap.
Vacuum has the advantage of being an isolator for heat transfer via both conduction and convection, meanwhile radiation can pass through it reaching the aluminum sheet and heating it up.

D. Wind power added by Savonius turbine
Savonius turbine is fitted on the top of the model and distant 30 cm from its top in order to acquire more power generation through wind energy. This will enhance the power generated by the system especially when sun sets and in night times where no sun rays exists.

IV. DESIGN EQUATIONS AND CALCULATIONS
A. Solar Chimney Air flow power equations

\[ \Delta Pd = Pa\left(\frac{1}{Ta} - \frac{1}{Te}\right) \times H \times g \]  
(Pressure difference equation)

\[ Q = m \cdot C_p \cdot (T_a - T_e) \]  
(Air Heat transfer equation)

\[ \nu_e = \sqrt{\frac{2 \cdot \Delta Pd}{\rho}} \]  
(Air Exit velocity equation)

\[ P = \frac{1}{2} \eta_T \cdot \rho_e \cdot A_e \cdot \left(\nu_e\right)^3 \]  
(Power equation)

Where:
\( \Delta Pd \): Pressure difference. \( \rho_e \): Out let Air Density.
\( T_e \): Average exit air temperature. \( T_a \): Inlet air temperature.
\( Pa \): Atmospheric pressure. \( \rho \): Ambient Air Density.
\( H \): Height of the tower. \( \nu_e \): Exit Air Velocity
\( Ra \): Universal gas constant for air. \( P \): Output Power.
\( g \): Gravitational acceleration. \( A_e \): Exit Area
\( \eta_T \): Air Turbine efficiency.

B. Heat transfer equations through every wall
Figure 6. Heat transfer study interfaces per window

a. Interface(1) air flow with aluminum sheet.
   \[ Q_{\text{Cond Al}} + Q_{\text{RadAl/Air flow}} = Q_{\text{ConvAl/Air flow}} \]

b. Interface(2) aluminum sheet with stagnant fluid or vacuum.
   \[ Q_{\text{Rad Sun Trans}} = Q_{\text{Cond Al}} + Q_{\text{Cond Stagnated fluid}} + Q_{\text{Rad Al/Stagnated fluid}} \]

c. Interface(3) stagnant fluid or vacuum with glass sheet
   \[ Q_{\text{Cond Glass}} + Q_{\text{Rad Glass}} = Q_{\text{Cond Stagnated fluid}} + Q_{\text{Rad Al}} \]

d. Interface(4) glass sheet with ambient.
   \[ Q_{\text{Conv Ambient}} + Q_{\text{Rad Solar/Glass}} = Q_{\text{Cond Glass}} + Q_{\text{Rad Al/Glass}} + Q_{\text{Rad Sun Absorbed/Glass}} + Q_{\text{Rad Sun Transmitted/Glass}} \]

Where:

- \( Q_{\text{Cond Al}} \): Conduction heat transfer through aluminum sheet.
- \( Q_{\text{RadAl/Air flow}} \): Radiation heat transfer from aluminum to air flow.
- \( Q_{\text{ConvAl/Air flow}} \): Convection heat transfer from aluminum to air flow.
- \( Q_{\text{Rad Sun Trans}} \): Radiation heat energy transmitted through the glass.
- \( Q_{\text{Cond Stagnated fluid}} \): Conduction heat transfer through stagnant fluid.
- \( Q_{\text{Rad Al/Stagnated fluid}} \): Radiation heat transfer from aluminum to stagnant fluid.
- \( Q_{\text{Conv Ambient}} \): Convection heat transfer through glass.
- \( Q_{\text{Rad Solar/Glass}} \): Radiation Heat transfer from Sun to Glass outer surface.
- \( Q_{\text{Rad Al/Glass}} \): Radiation Heat transfer from Aluminum to Glass.
- \( Q_{\text{Rad Sun Absorbed/Glass}} \): Solar Radiation absorbed by the Glass.
- \( Q_{\text{Rad Sun Reflected/Glass}} \): Solar Radiation reflected by the Glass.
- \( Q_{\text{Rad Sun Transmitted/Glass}} \): Solar Radiation transmitted through the Glass.
V. EXPERIMENT LIMITATIONS

The heat added to the system depends on the type of trapped stagnant fluid/vacuum (air, helium or vacuum) which mainly rely on well evacuation for the window Gap with well isolation to avoid any leak in or out of the gap. Although the evacuation of the gap could be easily achieved by an evacuation pump that could give high values for negative pressure but that was limited by the fact that the trapping system would fail due to either collapse of the glass face, aluminum face or even losing the adhesion of silicon with either the glass or aluminum face which would certainly lead to system gas leakage or losing vacuum inside the gap.

Another limitation for the case of either filling helium or air in the gap related to pressurizing the system as this also would lead to either break the glass face, swell the aluminum face or cause system leak out.

For the Savonius turbine the generated power would increase with the number, height and diameter of blades and limitation in this case would be mainly related to the fact that this increase in such mentioned parameters would generate vibrations and stresses on the Solar tower system with the Savonius on top of it and this may lead to glass damage or system leak.

VI. INPUT DATA AND INPUT COMBINATION

Table 1 presents the input parameters and the experiment measurable and calculated outputs.

<table>
<thead>
<tr>
<th>Model</th>
<th>Measured Inputs</th>
<th>Measured Outputs</th>
<th>Related calculated Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar chimney tower</td>
<td>Ambient temperature.</td>
<td>Solar chimney tower exit temperature.</td>
<td>Pressure difference over the solar chimney tower.</td>
</tr>
<tr>
<td></td>
<td>Double face window different</td>
<td></td>
<td>Mechanical power generated over the solar chimney tower.</td>
</tr>
<tr>
<td></td>
<td>temperature distribution.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Savonius turbine</td>
<td>Wind speed rotating the direct</td>
<td>Generated voltage.</td>
<td>Electrical power.</td>
</tr>
<tr>
<td></td>
<td>current motor</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1 - Input (Design parameters) and the experiment output

Measurements were taken all over the day for both temperatures and wind generated voltage to see how the loss of power generated by the solar chimney tower would be compensated by the Savonius wind turbine generated power.

VII. RESULTS AND DISCUSSIONS

Experiment was held on 3 cases of wall gap filling (air, vacuum & helium), in addition Savonius voltage generated was recorded as well along with every case experiment.

Experiment 1. Heating up air Flow using stagnant air in wall gap.

In First case, stagnant air (Thermal conductivity 0.0262 KW/MK@ 25 deg C) will be used as the stagnated fluid in between the double wall window.

Below chart shows temperature records on the 12-April-2018 from 6 am till 6 pm.
Figure 7. Stagnant air window temperature variance

Figure 7 shows that at 1:42 pm the maximum inner aluminum sheet (facing inner air flow) temperature was 53.9 deg C at an ambient temperature of 23.9 deg C (30 degree C rise), this is corresponding to an average of 27.87 deg C rise in ambient temperature. Also average difference between aluminum inner surface temperature and inner glass surface temperature was 12.85 deg C.

Figure 8. Ambient and tower exit temperature difference for stagnant air Case

Figure 8 shows that the average temperature rise between ambient and tower exit temperature was 8.15 deg C.

Experiment 2. Heating up air Flow using stagnant helium in wall gap.
Second experiment was held with stagnant helium (Thermal conductivity 0.1493 W/m. □ C@ 25 □ C) as the stagnant fluid in between the double wall window. On the 13th Of April-2018, temperature measurements were taken all over the day light for several points on the solar chimney along with ambient temperature showing the following results plotted on the chart below.
**Fig 9. Ambient and tower exit temperature difference for stagnant helium case**

Figure 9 shows that at 1:14 pm the maximum inner aluminum sheet (facing inner air flow) temperature was 55 deg C at an ambient temperature of 27 deg C (28 deg C rise) this is corresponding to an average of 26.97 deg C rise in ambient temperature. Also average difference between aluminum inner surface temperature and inner glass surface temperature was 3.78 deg C.

**Fig 10. Ambient and tower exit temperature difference for stagnant helium case**

Figure 10 shows that the average temperature rise between ambient and tower exit temperature was 6.7 deg.

**Experiment 3. Heating up air Flow using vacuum in wall gap (vacuum Window).**

Third experiment was held after vacuuming the gap between the double wall windows. On the 14th Of April-2018, temperature measurements were taken all over the day light for several points on the solar chimney tower along with ambient temperature showing the following results plotted on the chart below.
Figure 11 shows that at 14:02 pm the maximum inner aluminum sheet (facing inner air flow) temperature was 64.58 deg C at an ambient temperature of 26.13 deg C (38.45 deg C raise up) this is corresponding to an average of 36.83 deg C rise in ambient temperature. Also average difference between aluminum inner surface temperature and inner glass surface temperature was 45.001 deg C.

Figure 12 shows that the average temperature rise between ambient and tower exit temperature was 11.75 deg.

**Experiment 4. Measuring generated voltage by the Savonius wind turbine**

Over the previous 3 days of measuring the effect of different fluid/vacuum temperature effect and in parallel the Savonius turbine generated voltage was measured showing the following results:
Over the 3 target recording days (every day corresponds to one of the above solar tower experiment with different fluid in the gap).

Wind generated energy was recorded in form of voltage readings, the readings were fluctuating according to wind speed to vary from 2.6 volts to 0 volt.
VIII. SYSTEM POWER CALCULATIONS

![Solar Tower Energy Comparison](image1.png) ![Savonius Energy Comparison](image2.png)

Fig 16. (a) Solar tower gained energy comparison for the 3 cases and (b) Savonius gained energy comparison over the 3 days of the experiment

<table>
<thead>
<tr>
<th>Date</th>
<th>Solar Tower gap Media</th>
<th>Total Calculated Electrical Energy gained by Solar Tower (Watt hr.)</th>
<th>Total Calculated Electrical Energy gained by Savonius Turbine (Watt hr.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12-Apr-18</td>
<td>Air in Gap</td>
<td>0.12483</td>
<td>16.8365</td>
</tr>
<tr>
<td>13-Apr-18</td>
<td>Helium in Gap</td>
<td>0.083856</td>
<td>14.7695</td>
</tr>
<tr>
<td>14-Apr-18</td>
<td>Vacuum in Gap</td>
<td>0.20598</td>
<td>21.6719</td>
</tr>
</tbody>
</table>

Table 2. Total calculated electrical energy gained for solar chimney tower and Savonius wind turbine.

From the above charts and table, the following was noticed:

- Energy generated by Savonius is relatively high when compared to energy generated by Solar tower which is logic as the optimum dimensions for both models to produce the same amount of energy isn’t achieved as the commercial model of the solar chimney tower is reaching 100 meters height.
- For the solar chimney tower, energy produced in vacuum filled gap case is the greatest value when compared to air gap filled case that is greater than helium gap filled case.

IX. CONCLUSION

This research point was raised to study the effect of having different types of media fill for solar chimney tower windows facing Sun (air, helium and vacuum) on enhancing the power gained by this tower. The above study proved experimentally that the most efficient window gap filling is the vacuum, this is can be explained by the fact that vacuum isolates heat leak by conduction to the glass which in turn allows more heating up for the aluminum sheet that would supply more heat up for the air flow and more power generated from the fan.

On the other hand filling the window gap with helium didn’t show much improvement than filling it with air, on the contrary Helium gave less rise in ambient and exit air flow temperature rise than that for air filling gap case which can be explained by the fact that air conductivity is less than that for helium and hence more heat will be lost for the glass by conduction from the aluminum sheet.

Also, having the Savonius wind turbine on the top of the tower showed that it would be with a high benefit of adding power to the system but in order to maintain good comparison between both power sources (Solar chimney tower and Savonius wind turbine) the dimensions for both models should be adjusted to match real scale as the Solar tower chimney commercial model to produce beneficial electrical power usually has at least 100 meters height and in this case fitting the Savonius on the top of such tower will need to be considered as the whole construction design then must match the
weight, vibrations and stresses resulted from having the rotating Savonius wind turbine on the top of the solar chimney tower.

REFERENCES
V. F. Sigernes, “Savonius wind rotor basics”, University Centre in Svalbard (UNIS), Norway.