Design of an exhaust air energy recovery wind turbine generator for energy conservation in commercial buildings

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Abstract

The exhaust air energy recovery wind turbine generator is an on-site clean energy generator that utilizes the advantages of discharged air which is strong, consistent and predictable. Two vertical axis wind turbines (VAWTs) in cross-wind orientation which are integrated with an enclosure are installed above a cooling tower to harness the discharged wind for electricity generation. It is mounted at a specific distance and position above the cooling tower outlet. The enclosure (consisting of several guide-vanes and diffuser-plates) acts as a wind power-augmentation device to improve the performance of the VAWTs. The guide-vanes are placed in between the discharged air outlet and the wind turbine. They are designed to guide the oncoming wind stream to an optimum flow angle before it interacts with the rotor blades. The diffuser-plates are built extended from the outlet duct of the exhaust air system. They are tilted at an optimum angle to draw more wind and accelerate the discharged airflow. A particular concern related to public safety which may be due to blade failure is minimized since the VAWTs are contained inside the enclosure. The performance of the VAWTs and its effects on the cooling tower’s air intake speed and current consumption of the power-driven fan were investigated. A laboratory test was conducted to evaluate the effectiveness of the energy recovery wind turbine (5-bladed H-rotor with 0.3 m diameter) generator on a cooling tower model. The results showed a reduction in the power consumption of the fan motor for cooling tower with energy recovery turbine compared to the normal cooling tower. Meanwhile, the VAWT’s performance was improved by a 7% increase in rotational speed and 41% reduction in response time (time needed for the turbine to reach maximum rotational speed) with the integration of the enclosure. This system can be used as a supplementary power for building lighting or fed into electricity grid for energy demand in urban building. The energy output is predictable and consistent, allowing simpler design of the downstream system. The fact that there are an abundance of cooling tower applications and unnatural exhaust air resources globally causes this to have great market potential.

Keywords: Building integrated wind turbine; Exhaust air system; Energy Recovery; Power augmentation; Urban wind energy

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1. **Introduction**

Dependency on fossil based energy resources leads to the energy crisis due to depletion of these resources. Increase of population and economic growth contribute to higher demands of energy that only worsens the situation. Therefore, one of the most important concerns globally is the need of energy security. Energy generation from renewable resources such as wind, solar, tidal and biomass is one of the options to reduce the dependency on fossil resources. The idea of on-site renewable energy generation is another great approach where the energy is extracted from renewable sources close to the populated area where the energy is required. However, renewable energy generations are highly dependent on geographical conditions.

Urban areas are the places where energy is needed most. In Malaysia, at an urban area, the wind speed is less than 4 m/s for more than 90% of the total hours in a year [1]. This value is not conducive for on-site energy generation from wind. However, in this paper, an innovative idea to generate clean energy from alternative wind resources in urban areas is presented. The alternative source of wind is from the exhaust air systems.

Cooling tower is one of the most common exhaust air systems that is used to dissipate heat from power generation units, water-cooled refrigeration, air conditioning and industrial processes [2]. It is a device used to transfer waste heat to the atmosphere; large office buildings, hospitals and schools typically install one or more cooling towers for the building ventilation system. The idea of this project is to develop an energy recovery system by installing vertical axis wind turbines (VAWTs) at the outlet of the cooling tower to generate electricity from the wasted discharged air. The VAWTs is surrounded by enclosures to improve the performance as well as the air flow of the cooling tower.

However, it is essential to ensure that this additional feature does not provide a negative impact to the cooling tower. An optimized cooling tower has the optimum ratio of the mass rate of flow of circulating water to the mass rate of flow of dry air [3]. For the case of this energy recovery turbine generator, only parameters related to the dry air, i.e. mass flow rate, fan rotational speed, intake speed, outlet speed and fan motor power consumption might be affected. This paper reports the results for the experiments that have been conducted in developing the energy recovery turbine generator.
2. Literature Review

2.1 Factors that affect cooling tower performance and performance testing on an induced-draft cooling tower

Direct-contact induced-draft cooling towers are the most common cooling tower in Malaysia. Figure 1 shows an example of a cross-flow direct-contact induced-draft cooling tower. This type of cooling tower relies on power-driven fans to draw or force the air through the tower. The air enters the cooling tower through the louver at the sides of the tower. Then, it is forced to flow upwards until the exit on top of the tower and at the same time, it is in contact with the water that is flowing downwards. The cross-flow heat transfer from water to the air happens when they are in contact. The heat in the air is then released to the atmosphere at high speed through the outlet channel. Wind speeds up to 18 m/s is recorded at a distance 0.3 meter above the outlet the of cooling tower, which is preferable to generate electricity [4].

![Figure 1 Cross-flow direct-contact induced-draft cooling tower](image)

There are a lot of factors which affect the cooling tower air flow performance, i.e. interference and recirculation. Interference happens when a portion of the wind from the outlet of a cooling tower contaminates with the air intake of the other cooling tower [6]. Therefore, a proper design especially on the discharge height and the distance between the cooling towers is necessary to minimize the interference. On the other hand, recirculation or
sometimes called re-entrainment is another undesirable situation that affects the performance of a cooling tower. The basic principle of the cooling tower is to take the fresh ambient air into the compartment for the air to absorb and carry the heat out of the cooling tower through the outlet. If the discharged air is recirculated by contamination with the intake air, the performance of the cooling tower will be affected. The potential for recirculation is primarily related to ambient wind force and direction. It tends to increase as the ambient wind velocity increases [6]. When the strong wind blows towards the cooling tower, the discharge air is forced to change direction and causes it to contaminate with the intake air.

There are many factors that affect the cooling tower performance such as water distribution, air distribution, water inlet and outlet temperature, etc. However, in case of troubleshooting, fan flow characteristic is one of the first items to be investigated. In order to evaluate the performance of the fan, the parameters to be measured are the air flow rate, power input to motor and fan speed [7].

2.2 The use of diffuser to improve wind turbine performance

Besides focusing on improving the performance of the wind turbine by the aerodynamic study of the turbine blades, increasing the on-coming wind speed before it interacts with the wind turbine also provides a significant result in power generation increment. The power in the wind is proportional to the cube of the wind speed, which means that even a small increment in wind speed gives a large increase in energy generation. Therefore, many researchers had studied and reported different designs of ducted or diffuser augmented wind turbines, which increase the on-coming wind speed hence increasing the efficiency and performance of turbines. Mass flow augmentation can be achieved through two basic principles, i.e. increase in the diffuser exit ratio or decrease the negative back pressure at the exit or both [8]. A diffuser has a duct surrounding the turbine blades and it essentially raises the back pressure of the turbine and causes a negative pressure at the back. The back pressure draws more accelerated wind through the blade plane, and hence more power can be generated compared to a turbine without diffuser at the same rotor blade size.

The Small-Scale Wind Energy Portable Turbine (SWEPT) concept of Kishore et al., is designed for a target to operate below 5 m/s. The use of diffuser to the SWEPT of the same size produced 1.4 to 1.6 higher electrical power compared to the SWEPT without diffuser [9]. Kosasih and Tondelli have conducted investigations on several types of diffuser. Compared to a turbine without diffuser, the coefficient of performance of the micro wind turbine
increased by approximately 60% with the addition of a simple conical diffuser, and 63% with the addition of a nozzle-conical diffuser shroud [10]. Another diffuser design is a diffuser with flange of Ohya et al. [11]. With the optimum length of flange, the diffuser successfully produced a remarkable increase in wind speed of 1.6–2.4 times that of the approaching wind speed. A complete system of wind-solar and rainwater harvester of Chong et al. also applies the diffuser design for wind power augmentation. Preferable to the vertical axis wind turbines, the system is able to increase the power generation by a VAWT up to 3.48 times compared to the bare VAWT [12, 13].

3. Design Description

The exhaust air energy recovery wind turbine generator is a novel idea on generating green energy by harnessing unnatural wind resources using micro wind generation system. The unnatural wind resources can be from a cooling tower, air ventilation system, humidification plant or any system that produces strong and consistent winds. However, the integration of the exhaust air energy recovery wind turbine generator is not identical to all the unnatural wind resources. This is due to different systems having different characteristics and geometry. A specific configuration has to be designed in order to recover the maximum amount of energy from the exhaust air system without any significant negative effect to the original system. In this paper, the exhaust air energy recovery wind turbine generator is specifically designed for integration with a cooling tower. Figure 2 shows the general arrangement of this innovative system.

![Figure 2 General arrangement of the exhaust air energy recovery wind turbine generator](image)
Two vertical axis wind turbines (VAWTs) in cross-wind orientation were integrated with an enclosure, and installed at the outlet of a cooling tower to harness the discharged wind for electricity generation. Based on the discharged air wind speed profile, the turbines are positioned so that the highest wind speed is facing the positive torque sector of the wind turbines. The distance between the cooling tower outlet to the nearest turbine circumference is set to be at least half of the rotor diameter to minimize the blockage effect.

To enhance the performance, the VAWTs are surrounded by an enclosure. The enclosure is constructed with the combination of a diffuser, several guide-vanes and safety grills. The diffuser plays the role of concentrating and accelerating the approaching wind to the wind turbine. The resulting sub-atmospheric pressure within the diffuser draws more air through the blade plane, and hence more power can be generated compared to a turbine without diffuser of the same rotor blade diameter [14]. The diffuser alters the flow field, increasing the volume of fluid passing through the turbine, and hence the velocity [15]. For the case of installing the diffuser at the outlet of an exhaust air system, it would help to improve the flow of the system. Figure 3 illustrates an artist’s impression of the exhaust air wind energy recovery turbine generator at the outlet of a cooling tower on the roof top of a building.

Figure 3 An artist’s impression of the exhaust air wind energy recovery turbine generator at the outlet of a cooling tower on the roof top of a building.
The guide-vanes are in the position of the flow entrance to the enclosure. The vanes form multiple flow channels which are utilized to speed up the wind stream by creating a venturi effect and to guide the wind stream to the optimized angle of attack of the VAWT blades. It is adapted from the authors’ previous design [13, 16]. For safety purpose, the other side of the enclosure is surrounded by safety grills for hazard prevention. In case of blade failure, there is no possibility for the blades to fly off and cause injury to the people around since it is contained inside the enclosure.

4. Methodology

The effect of installing the energy recovery turbine generator at the outlet of an exhaust air system was investigated via laboratory test on a scaled model of a cooling tower. The cooling tower model is shown in Figure 4. It was constructed similar to the general arrangement of a common cooling tower with the air inlet at the bottom and powered by a 0.7 m industrial fan. The gap for air inlet at the bottom was 0.195 m from the floor. The wall, pillars and air duct were made of fiber reinforced plastic (FRP), by courtesy of Truwater Cooling Towers Sdn. Bhd. The test was conducted in three configurations, i.e. i) cooling tower only, ii) cooling tower with VAWT, and iii) cooling tower with VAWT and enclosure. The configurations are depicted in Figure 5.

Figure 4 Picture of cooling tower model for laboratory test
4.1 Laboratory test: Cooling tower only

The experiment for cooling tower only was set as the baseline for the other configurations. This is because the result for this experiment represents the original performance of a cooling tower without any additional feature. Four parameters were measured to evaluate the cooling tower air flow performance, i.e. inlet air speed, discharged air speed, fan rotational speed and power consumption by the fan motor. Hot-wire anemometer was used to measure the inlet and discharged air speed. The inlet air speed were measured at the air entrance on each side of the cooling tower while the outlet air speed were measured in 5 bands of equal areas which were divided into 8 sectors. The fan rotational speed and motor power consumption were measured by laser tachometer and clamp-on multimeter respectively.

4.2 Laboratory test: Cooling tower with VAWTs

The second configuration was with the VAWTs installed at the outlet of the cooling tower model. In this experiment, two 5-bladed H-rotor turbine with FX 63-137 airfoil blades with a diameter of 0.3 m were placed at a predefined position in cross-wind orientation facing the discharged wind. The VAWTs were in a symmetrical order with the vertical distance between the discharge outlet duct to the center of the turbine at 0.26 m. The horizontal distance between the center of the outlet duct to the center of the turbine is set to be 0.23 m. All the parameters that were measured in the first configuration (cooling tower only), were repeated in the second configuration. Two additional parameters were measured in this configuration, i.e. VAWTs rotational speed and response time. The rotational speed measurement was done using a laser tachometer. The VAWT response time is the time needed for the VAWT to achieve its stable rotational speed.
4.3 Laboratory test: cooling tower with VAWTs and enclosure

In this configuration, the VAWTs were surrounded by the enclosure. As mentioned in the design description section, the enclosure is built with a combination of diffuser and guide-vanes. At this moment, all the guide-vane angles were set to be 90° relative to the discharged wind direction which are not the optimized angles. The study on optimization of guide-vane angles is not included in this paper. All the measurements in the second configuration were repeated in the experiment on cooling tower with VAWTs and enclosure.

5. Results and discussion

The results from all the three configurations are compared with the first configuration which is considered the baseline for the experiment where it represents the performance of an original cooling tower without any additional feature. The results are tabulated in Table 1.

<table>
<thead>
<tr>
<th>Test configuration</th>
<th>Intake wind speed (m/s)</th>
<th>Fan motor power input (W)</th>
<th>Fan rotational speed (rpm)</th>
<th>Rotational speed (rpm)</th>
<th>Response time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling tower only</td>
<td>1.90</td>
<td>203.84</td>
<td>1364.33</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Cooling tower with VAWTs</td>
<td>2.15</td>
<td>200.20</td>
<td>1366.00</td>
<td>438.0</td>
<td>101.7</td>
</tr>
<tr>
<td>Cooling tower with VAWTs and enclosure</td>
<td>2.52</td>
<td>198.86</td>
<td>1369.67</td>
<td>472.2</td>
<td>59.6</td>
</tr>
</tbody>
</table>

The original cooling tower model performance is considered when there was no additional feature on the model. In this condition, the intake wind speed was 1.90 m/s, fan rotational speed was 1364.33 rpm and the power consumption by the fan motor was 203.84 W. When the VAWTs were installed at the outlet of the cooling tower model, the average maximum rotational wind speed was 441 rpm while the response times were 102 seconds and 150 seconds for VAWT 1 and VAWT 2 respectively. The difference in response time may be due to the mechanical loss in the wind turbines (friction loss). The intake wind speed increased to 2.15 m/s while the power consumption dropped to 200.20 W. Theoretically, this may be due to the speed of the turbines being faster than the discharged wind speed. When
the speed of the turbine was higher than the incoming wind, a low pressure region was created surrounding the wind turbine swept area, which may help the cooling tower to draw more air due to the suction effect. This condition contributed to the increase in intake wind speed and reduction of fan motor power consumption. There was a small increase in rotational speed of the fan, i.e. 0.1% with this configuration.

When the enclosure was in place with the VAWTs, the performance of the cooling tower model and VAWTs were further improved. The intake air speed was increased by 17% and the fan motor power consumption was reduced by 0.7% compared with the configuration of VAWTs without enclosure. The average rotational speed for the VAWTs was 474 rpm while the response times were reduced by 41% for both VAWT 1 and VAWT 2. The fan rotational speed also increased to about 1369 rpm for the cooling tower with turbine and enclosure. These results proved that the enclosure has served its purposed to improve the air flow which consequently improved the performance of the cooling tower model and VAWTs.

6. Conclusion

An energy recovery wind turbine generator for energy conservation in commercial buildings has been presented. It is considered as an energy recovery system where it generates energy from the wasted wind from an exhaust air system to provide an alternative source of electricity to the building. It is designed so that it does not caused any negative impact to the performance of the original exhaust air system. The energy recovery turbine generator is the combination of two VAWTs surrounded by an enclosure and installed at the outlet of an exhaust air system. The VAWTs are placed at a predefined position for optimum performance while the enclosure also helps to improve the performance of the VAWTs as well as the exhaust system air flow.

From the laboratory test, it was observed that installing VAWTs at a correct position above the exhaust air system does not give any significant negative impacts on the performance of the cooling tower model. The performance of the cooling tower model was improved by the increment of intake air speed and the reduction of fan motor power consumption. The rotational speed of the VAWTs was very high (> 400 rpm) while the tip speed ratios were in the range of 1.28 – 1.29, making it preferable for electricity generation. The integration of the enclosure provided further improvements in all aspects. With the enclosure, the VAWTs rotational speed were increased on average by 7% while the response times were significantly reduced by 41%. The intake air speed of the cooling tower model
was increased and the power consumption was reduced. Since the fan rotational speed and intake air speed have increased, and the fan motor power consumption has decreased, the integration of the exhaust air wind energy recovery turbine generator at the outlet of a cooling tower is considered as providing a positive effect to the cooling tower performance. However, the fan performance curve need to be studied since this system affects the fan characteristic and the fan operating point would have changed.

Installing this exhaust air wind energy recovery turbine generator is highly recommended for energy conservation in commercial buildings. It is not only capable of generating electricity constantly when an exhaust system is in operation but also reduce the power consumption by the exhaust air system. A commercial building with this innovative system in place, would have an increase in value and rating because it could be awarded a higher certification in green building index evaluation. It is an energy recovery system and not intended to replace fossil fuel for energy demand of a country. However, this system enables the low wind speed countries especially in urban areas to harness wind energy from exhaust air resources which are consistent and predictable. The electricity generated from this system can be used for commercial purposes or fed into the electricity grid. It is retrofit-able to existing cooling towers and has very high market potential due to abundance of unnatural exhaust air resources globally.

7. Acknowledgement

The authors would like to thank the University of Malaya for the facilities and assistance provided in the patent application of this design (Patent pending: PI 2011700168). Sincere gratitude is also dedicated to the Malaysian Ministry of Higher Education (MOHE) for the Prototype Development Research Grant Scheme (PR002-2012A). Special appreciation is credited to Truwater Cooling Towers Sdn. Bhd. as an industrial partner for providing the facilities, fabrication materials, and manpower to perform the tests.

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