Early development of an energy recovery wind turbine generator for exhaust air system

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HIGHLIGHTS

- Exhaust air energy recovery system to recover part of the energy in discharged air.
- An innovative way to generate electricity and reduce CO₂ emission.
- Equipped with diffuser-plates and guide-vanes to improve wind turbine performance.
- Enclosure solves conventional wind turbine problems in urban areas.
- 13% of the energy consumed by the fan motor is expected to be recovered.

GRAPHICAL ABSTRACT

Abstract

An innovative idea on extracting clean energy from man-made wind resources with micro wind turbine system for power generation is introduced in this paper. This system generates on-site clean energy using a micro wind generation system. A vertical axis wind turbine (VAWT) with an enclosure is mounted above a cooling tower's exhaust fan to harness the wind energy for producing electricity. The VAWT is positioned at a specific position at the cooling tower outlet to avoid a negative impact on the performance of the cooling tower. The enclosure can act as a safety cover and also enhance the performance of the VAWT. It is designed with several guide-vanes positioned at the up-stream side of the wind turbine to create a venturi effect and guide the wind before it interacts with the turbine blades. Moreover, the enclosure design is comprised of diffuser-plates that can draw more wind and accelerate the flow. Laboratory test conducted on a scaled model shows no measurable difference in the air intake speed and current consumption of the power-driven fan when the turbine was spinning above the cooling tower. Field test on an actual induced-draft cooling tower shows no significant difference on the outlet air speed of the cooling tower. A small difference was observed on the power consumption by the fan motor which is 0.39% higher with the presence of the VAWT. This system is retrofit-able to existing cooling towers and has very high market potential due to abundant cooling towers and other unnatural exhaust air resources globally.

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1. Introduction

The massive growing rate of fossil fuel consumption and nuclear waste generation with their negative impacts of pollution has attracted worldwide attention to invest in researches and developments in renewable energy as an alternative energy source. The most environment-friendly types of renewable energy like solar energy and wind energy are recognized as the world’s fastest developing energy resources. They provide a clean, effective and sustainable technology. Today, the urgent need for renewable energy resources due to the increase in energy demand has resulted in continuous efforts and studies to establish more attractive energy generator systems which are better in terms of performance and economic aspect.

In Malaysia, the wind speed is low and inconsistent throughout the year (free-stream wind speed, $v_{inf} < 4 \text{ m/s}$ for more than 90% of total wind hours) [1]. The wind power operation is subjected to changing wind patterns which result from climate change since the wind condition is governed by both the Northeast and Southwest monsoons [2]. As a result, harnessing wind energy with conventional wind generators is not appropriate in Malaysia. In order to address this issue, a novel idea is presented in this paper; to extract wind energy from unnatural wind resources i.e. exhaust air system for electricity generation. The exhaust air characteristic from the exhaust outlet usually has strong and consistent wind speed compared to natural wind. Furthermore, there are many existing forced ventilated situations globally such as ventilated exhaust from air conditioning system [3]. These benefits will lead to the installation of a wind turbine generator at low wind speed regions to become applicable.

The feasibility of integrating the designed energy recovery wind turbine generator above an exhaust air system was evaluated by performing a series of tests on a fabricated small scaled model of cooling tower, followed by an actual unit of cooling tower provided by the manufacturer. The main purpose of the project is to generate clean energy from the exhaust air system without producing any negative impacts on the performance of the original exhaust air system. At the same time, this system is capable of recovering a portion of the power consumption by the cooling tower fan motor.

2. Wind power generator improvement

The utilization of wind power is growing rapidly due to technological improvements, industry maturation and an increasing concern with greenhouse gas emissions associated with fossil fuels. It is one of the least expensive renewable energy resources to generate electricity without CO$_2$ emission with a growing rate of 30% annually [4,5].

Wind power is well known to be directly proportional to the cube of wind speed approaching a wind turbine [6]. This means that with a slight acceleration in wind speed, it will cause a large increase in the wind power output. Hence, there are numerous researches being done to find ways to effectively improve the approaching wind speed. Matsushima et al. conducted a study on the effect of output power generated from a small wind turbine system after adding a diffuser. Based on the experimental results, maximum wind speed was increased by 1.7 times with the appropriate selection of diffuser shape [7]. There was also an experiment carried out by Ohyz et al. which showed that the performance of a diffuser shrouded with a broad-ring flange at the exit periphery of a wind turbine system is better in terms of power coefficient [8]. The flanged-diffuser shroud helps to collect and accelerate the approaching wind with a low pressure region generated at the rear of the turbine by creating a separation region [9]. The low pressure region appears to allow greater mass flow through the turbine in contrast to a bare wind turbine [10]. As a result, the volumetric flow rate of the wind through the rotor increases and a higher energy output was achieved. Based on the study conducted by Van Bussel, he discovered that the power augmentation is proportional to the mass flow generated at the nozzle of the diffuser augmented wind turbine [11]. Hence, the outlet/inlet area ratio and the length of the air flow path over which diffusion occurs are critical to determine the diffuser efficiency [12].

In addition, a guide-vane system can be integrated with the wind turbine system to further improve the approaching wind speed to the turbine. It is done by directing approaching air into the moving blades with minimum loss of energy. Chong et al. had designed a 3-in-1 wind-solar hybrid renewable energy and rainwater harvester with a wind turbine integrated with a power-augmentation-guide-vane (PAGV). The rotational speed of the VAWT was increased by 73.2% at a wind speed of 3 m/s for the case with the PAGV compared to a bare wind turbine [13]. Furthermore, the PAGV was further improved to collect the on-coming wind from any direction and it is known as an omni-direction-guide-vane (ODGV) [14]. From the CFD simulations, output power of a single-bladed VAWT was improved by 206% at a tip speed ratio of 0.4 with the presence of the ODGV. The geometry of the guide-vane also plays an important role in improving the wind turbine system efficiency. By referring to the study conducted by Takao et al., the power coefficient and the torque coefficient of a wind turbine system depends on the distance between the guide-vanes [15].

In this paper, both diffusers and guide-vanes were utilized to form an enclosure and integrated with the wind turbine system above the cooling tower’s outlet to improve the output power generated by the VAWT. The performance of the VAWT and its effect on the cooling tower’s performance were investigated to identify the effectiveness of the enclosure. From the feasibility study, a higher capacity factor can be achieved compared to the identical VAWT that generate power from natural wind in urban areas.

3. Review of cooling tower system

On-land locations with sufficient wind speeds to install wind farm will become limited owing to the size of the rotor diameter
having increased tenfold over the years [16]. The new trend is to install wind turbines within a building structure or above a high rise building. Wind turbines that are incorporated within a building environment are described as building integrated wind turbines (BIWTs). BIWTs are encouraged for urban on-site clean energy generation as renewable energy is directly supplied to the building where the energy is needed, allowing a notable contribution to a sustainable design of new buildings in terms of energy consumption [17]. Besides, it has the potential of reducing CO2 emissions that may cause significant impacts on global climate change [18].

Cooling towers are the good candidates for wind power extraction. They play an important role as heat removal devices that make use of water and air through the evaporation process to reject waste heat to the atmosphere. The most common type of cooling tower used in Malaysia is the mechanically induced draft tower. The ambient air is drawn into the tower and heated air is forced out from the outlet of the cooling tower with the assistance of power-driven fans. The exhaust air is suitable for electricity generation as it can go up to 18 m/s recorded at a distance of 0.3 m above the cooling tower outlet [19]. These towers are widely installed at thermal plants, oil refineries, and large office buildings such as hospitals and schools for building ventilation purposes [20].

Power is drawn by the cooling tower fan to spin the propeller type fan and obtain the correct air flow movement through a cooling tower. Usually, the fan is designed to be at least twice the applied power in order to deliver equivalent air flow against the low static pressure in the cooling tower [21]. With the installation of an energy recovery system above the cooling tower’s outlet, a part of the fan motor power consumption could be recovered and the exhaust air system discharge improved. It also does not need an extra land area for the installation and thus it makes it advantageous compared to the conventional wind energy systems. Factors that greatly affect the performance of cooling towers such as interference, recirculation, and position of the VAWT will be considered in order to achieve harmony between the installation of the energy recovery wind turbine system and the operation of the cooling tower.

4. Design description of the energy recovery wind turbine generator

4.1. General arrangement and working principles of the system

With the technical know-how on Bernoulli’s principle and vertical axis wind turbine operating characteristics, the design of this energy recovery system was developed. The general arrangement of this innovative system is illustrated in Fig. 1. A VAWT (in cross-wind orientation) that is integrated with an enclosure is mounted above a cooling tower outlet by a supportive structure to extract the wind energy. The supporting structure is the main structure to hold the VAWT, guide-vanes and enclosure. It can be installed above any ventilation outlet either in a horizontal or vertical position depending on the direction of the approaching wind. A predefined location for positioning the VAWT facing the cooling tower’s outlet is essential to ensure zero or minimum negative effect on the performance of the original system. The radial position (on elevated plane above the exhaust air outlet) of the VAWT was set to match with the exhaust air speed profile. Portion of the VAWT blades rotating path was located slightly out of the discharged air stream (slightly out of the cooling tower exhaust outlet) so that the highest wind speed can interact with the wind turbine blades at the positive torque areas and hence maximizes the VAWT performance. The selection of wind turbine type and size is also critical to ensure its operation would not cause the blockage effect to the original exhaust air system. The VAWT tip speed ratio (TSR) is designed to be in a certain range (TSR = 3–6) in order to develop a low pressure region for inducing more air from the exhaust air outlet. It can be installed horizontally where it is supported at both ends of the power transmission shaft with the generator at a side in order to harness the outlet air that is blowing from the bottom. It is also able to be mounted in a vertical direction with the generator placed on the floor.

In order to maximize the energy recovery from the exhaust air, the enclosure is equipped with guide-vanes to guide the wind direction to an optimum angle of attack before it encounters the wind turbine. A venturi effect is established and causes a significant increase in the wind speed. This feature will greatly enhance the self-starting behavior of the VAWT and it is able to spin closer to its rated speed. Hence, the amount of electricity produced increases as rotational speed of the VAWT improves. Diffuser-plates are installed inclined outwardly at an optimum angle relative to their vertical axis at both sides of the VAWT. Air flow characteristic improvement can be obtained and more output power can be acquired as compared to a bare wind turbine since it has a higher power coefficient (4 times higher) [22].

In addition, the concern on the safety issue is minimized by integrating the wind turbine with an enclosure. The possibility of danger caused by blade failure can be reduced by using a layer of mesh to cover the enclosure. It blocks flying creatures like birds from striking the turbine. Since the VAWT is installed within the enclosure, the noise generated is lower and no negative visual impact is produced.

4.2. Benefits of the energy recovery wind turbine generator designed

This innovative system is aimed at generating on-site clean energy by converting wasted wind energy from a cooling tower to a useful form of energy. The energy generated is predictable and continuous because the exhaust wind is readily available whenever the cooling tower is switched on. In other words, exhaust air consists of wind characteristic that is predictable and consistent. Thus, statistical analysis of wind characteristic over a period of time is not required. In addition, the turbine is expected to spin at a constant rotational speed and therefore, over speed control is not necessary because only minimum rotational speed fluctuation is experienced. For that reason, the lifespan of the turbine is expected to be longer.

The efficiency of the wind turbine is greatly improved when it is integrated with an enclosure. Guide-vanes are equipped to guide the wind stream to an optimum angle of attack at the wind turbine. More air will be discharged and will interact with the wind turbine due to the suction effect resulting from the low pressure zone around the VAWT. This advantage promotes better self-starting behavior and the turbine is able to rotate faster at its rated speed. Besides, hazards during maintenance and installation can be
reduced to a great extent by integrating the VAWT with an enclosure. The enclosure can work as a safety cover because the turbine is enclosed within it.

This energy recovery system has a high market potential due to abundant usage of exhaust air systems. It is a green energy invention which investigates visionary and technology-driven solution that is able to supply a portion of the energy demand of a metropolis. Fig. 2 shows an artist’s impression of the energy recovery wind turbine generator mounted above an exhaust air system.

5. Methodology

The feasibility and conceptual design of the energy recovery system were validated by conducting a series of experimental tests including laboratory test on a scaled model and field test on an actual cooling tower. The system design and experimental set-ups were developed with the technical know-how on the VAWT and Bernoulli’s principle as described in Section 4. The effects of the energy recovery wind turbine system on the exhaust air performance and the performance of the VAWT are the main parameters to be investigated in the tests.

5.1. Indoor laboratory test on a small scaled model of cooling tower

The indoor experimental test was conducted in the Fluid Mechanics Laboratory, University of Malaya. Three conditions of experimental test were conducted which are:

(1) Cooling tower without wind turbine.
(2) Cooling tower with wind turbine.
(3) Cooling tower with wind turbine surrounded by enclosure.

Fig. 3 shows the experimental setup for the small scaled model. A 5-bladed H-rotor wind turbine with 0.3 m rotor diameter size was used and a 0.4 m diameter of industrial fan enclosed in a 0.6 m diameter cylinder duct represented the cooling tower. At the bottom of the cooling tower, there was a gap of 0.1 m from the floor. The wind turbine was placed within a 0.4 m diameter enclosure and 0.07 m above the industrial fan.

As recommended by Abe et al. [22], diffuser-plates are best when inclined at 7° relative to its vertical axis as this is the optimum angle. They were mounted at both ends of the wind turbine as shown in Fig. 4. Guide-vanes were set with the same orientation throughout the test and the effect was not studied in this paper. They were also used as a linking structure to hold the diffuser-plates. Maximum speed was set for the fan and the current drawn through the test and the effect was not studied in this paper.

5.2. Field test on an actual cooling tower

A field test was carried out to obtain reliable results on the performance of the energy recovery system and the cooling tower. The design and installation of the energy recovery wind turbine generator with the existing cooling tower is shown in Fig. 5. A trial run had been done before a comprehensive field test was conducted to verify the performance of the designed system above the cooling tower. The trial results showed that there was no measurable difference observed on the power consumption of the fan motor or the exhaust and inlet air speeds exerted on the cooling tower.

In this test, a combination of a 3-bladed Darrieus type VAWT with a rotor diameter of 1.24 m with two stages of Savonius rotor at the center shaft was mounted above a cooling tower (2 m outlet diameter). The shaft of the motor was positioned at a distance which gives the best performance of the VAWT based on the measured velocity profile from the exhaust air. There is an appropriate approach to set the minimum vertical distance between the nearest circumference (rotating path) of the VAWT and the outlet of the cooling tower at half of the diameter of the rotor. This configuration was obtained based on the trial run in the laboratory, and therefore it would not create a blockage to the original exhaust air system. This system was mounted on the supporting structure at both ends of the power transmission shaft with the generator at one side and bearing at the other. Field test was conducted under two conditions as below:

(1) Cooling tower without wind turbine.
(2) Cooling tower with wind turbine.

The volumetric flow rate from the exhaust air outlet was measured to identify the amount of blockage when an object is placed at the outlet of the cooling tower. It was calculated by the following equation:

\[ Q = \frac{v_{outlet} \times A_{outlet}}{60} \]  

where \( Q \) is the volume flow rate; \( v_{outlet} \) is the average wind speed measured at the cooling tower outlet and \( A_{outlet} \) is the outlet area.

The wind speed over the cross sectional area of the exhaust outlet will vary from point to point. A suitable measurement method for circular duct from Cooling Technology Institute (CTI) was adopted which divides the area into several concentric parts of equal region and the wind speed \( v_{outlet} \) is calculated by averaging six velocities taken at 60° intervals around the circle [23]. A laser tachometer was then pointed at the rotating shaft to measure the wind turbine rotational speed as shown in Fig. 6. The power consumption by the fan motor was measured by a 3-phase power analyzer.

6. Results and discussion

6.1. Indoor test on a small scaled model of cooling tower

The measured results for the indoor test are shown in Table 1. The wind speed at the cooling tower outlet was recorded at 8 m/s based on the set up of the small scaled model of cooling tower.
Under conventional cooling tower operating condition, the current consumption by the fan motor was 0.39 A and intake air velocity was in the range of 1.6–1.8 m/s. This condition was considered as the baseline throughout the entire experiment. Based on the test results, energy is extractable by installing the VAWT above the cooling tower outlet and it was recorded spinning at 115 rpm. Rotational speed of the VAWT was further improved by integrating with the diffuser-plates and it rotated at 150 rpm which was a 30.4% increment. There was no measurable difference detected on the current drawn by the fan motor and air intake velocity for all three test conditions. Since the rated power for the scaled model was too small, there were no significant differences observed on the additional load exerted on the fan motor nor negative impacts resulting from the energy recovery system.

6.2. Field test on an actual cooling tower

This outdoor experimental test was conducted to study wind speed profile released from the cooling tower, effects of energy recovery system on cooling tower and lastly, the performance of the installed wind turbine.
6.2.2. Cooling tower and wind turbine performance

Negative effect on the cooling tower air flow performance may come from the blocking effect when an object is placed in the exhaust air stream. This effect can be detected by the reduction of flow rate and an increase in the power consumption of the fan motor. The performance of the cooling tower and the wind speed behavior were compared for the cases before and after the installation of the energy recovery wind turbine generator above the cooling tower outlet. In addition, the distance of the nearest circumference of the VAWT to the exhaust air outlet was set to be at least half of the rotor diameter, i.e. 0.7 m to minimize the blockage effect to the air flow. Another factor that contributes to the blockage effect is the surrounding wind speed (uncontrollable variable). In this case, the surrounding wind speed was not considered for the field test.

6.2.3. Estimation of energy generated

In this study, an estimation of 3000 units of cooling tower is used in the energy generation calculation. This figure is tabulated as shown in Table 3. The optimized system with 2 units of wind turbine that is installed above a cooling tower is expected to generate 500 W from each of the rotors. Assuming that a 2 m diameter cooling tower requires 7.5 kW power for 16 h operation per day, 131.4 GW h/year of energy consumption will be utilized to operate 3000 similar units of cooling tower. With 1 kW of power generation by this exhaust air energy recovery wind turbine generator, a total of 17.5 GW h (for 3000 units of cooling tower) is expected to be recovered by the system in a year which is equivalent to 13% of the energy consumption of the cooling tower. The generated or recovered energy can be used as supplementary power for urban areas.

Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Cooling tower without wind turbine</th>
<th>Cooling tower with wind turbine</th>
<th>Percentage difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intake air velocity (m/s)</td>
<td>1.6–1.8 m/s</td>
<td>1.6–1.8 m/s</td>
<td></td>
</tr>
<tr>
<td>Wind turbine speed (rpm)</td>
<td>875</td>
<td>115 rpm</td>
<td>0.39</td>
</tr>
<tr>
<td>Discharged air velocity (m/s)</td>
<td>10.545</td>
<td>10.363</td>
<td>1.73</td>
</tr>
</tbody>
</table>

Wind turbine rotational speed measured when the RPM is stabilized.

As wind speed is proportional to air flow rate, the average discharged air speed was slightly decreased by 1.73% with the presence of the VAWT at the cooling tower outlet. At the same time, there was no significant difference observed on the power consumption of the fan motor where the increment was only 0.39% compared to the cooling tower without the VAWT. At free-running condition (no loading; only rotor inertia and bearing friction were applied), the VAWT rotated at 875 rpm while the exhaust wind speed from the cooling tower was approximate 10.363 m/s. The results had shown that the installation of the energy recovery turbine generator above the cooling tower produced minimum effects on the performance of the cooling tower. Careful considerations had been taken into account during the design stage i.e. the turbine’s solidity, tip speed ratio (TSR), and the distance to the exhaust air outlet in order to minimize the blockage effect. The selected Darrieus VAWT is a wind turbine that has a low solidity and high rotational speed operation. Since the solidity is low, the blockage effect exerted on the air flow is small. The TSR is 5.48 when the turbine was spinning at its stable rotational speed, which means that the turbine rotated more than 5 times faster than the on-coming wind. A low pressure region is expected to be created surrounding the VAWT causing more air to be sucked out from the cooling tower outlet. In addition, the distance of the nearest circumference of the VAWT to the exhaust air outlet was set to be at least half of the rotor diameter, i.e. 0.7 m to minimize the blockage effect to the air flow. Another factor that contributes to the blockage effect is the surrounding wind speed (uncontrollable variable). In this case, the surrounding wind speed was not considered for the field test.

6.2.1. Wind speed profile

The discharge air velocity was measured in five bands on every quarter. Fig. 7 demonstrates the average wind speed from each band. Highest wind speed was observed between band 3 and band 4. Band 1, where its location is near to the center of the outlet opening shows the lowest wind speed due to the position of the belting system being located above the cooling tower outlet which resulted in air flow resistance. Wind speed at band 5 (close to the outer radius) was low as well because there was a clearance between the blade tip and the inner wall duct (causing blade tip loss) when the exhaust air swirled and spread out from the fan [24]. By referring to the wind profile, it is best to locate the wind turbine at a position between band 3 and band 4 to match the optimum performance region of the wind turbine where the strongest wind speed can be obtained.

![Fig. 7. Discharged air profile from the cooling tower.](image)

Table 2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Cooling tower without wind turbine</th>
<th>Cooling tower with wind turbine</th>
<th>Percentage difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average discharged wind velocity (m/s)</td>
<td>10.545</td>
<td>10.363</td>
<td>1.73</td>
</tr>
<tr>
<td>Cooling tower fan rotational speed (rpm)</td>
<td>386.0</td>
<td>385.8</td>
<td>0.05</td>
</tr>
<tr>
<td>Fan motor power consumption (kW)</td>
<td>7.048</td>
<td>7.075</td>
<td>0.39</td>
</tr>
<tr>
<td>Wind turbine rotational speed (rpm)</td>
<td>875</td>
<td>–</td>
<td></td>
</tr>
</tbody>
</table>

Wind turbine rotational speed measured when the RPM is stabilized.

Please cite this article in press as: Chong WT et al. Early development of an energy recovery wind turbine generator for exhaust air system. Appl Energy (2013), http://dx.doi.org/10.1016/j.apenergy.2013.01.042
commercial buildings. In the tropics, air-conditioning system consumes the most power compared to other electrical system due to the hot and humid climate. Thus, as part of the air-conditioning system, cooling tower offers a lot of opportunities to implement this designed system especially in metropolitan area. In Malaysia, 1000–1500 units of new cooling tower are installed in a year according to the information provided by our collaborating partner, i.e., Truwater Cooling Tower Sdn. Bhd. (the largest cooling tower manufacturer in Malaysia). As a result, this energy recovery system (able to recover 13% of the fan motor power consumption) contributes significantly in energy savings as 57% of the energy is consumed by the air-conditioning system in commercial building in Malaysia [25].

7. Conclusions

An efficient on-site clean energy generation system that recovers unused wind resources from an exhaust air is designed. The energy recovery wind turbine generator is integrated with an enclosure which can act as a safety cover and also enhances the performance of the VAWT.

From the indoor test results, it was observed that installing a VAWT above the exhaust air system does not give any significant negative impacts on the performance of the cooling tower. The current drawn from the fan motor was 0.39 A for both cooling tower with and without the energy recovery turbine generator. The performance of the VAWT was greatly enhanced by 30.4% after integrating with an enclosure. A field test was conducted on an actual cooling tower to further examine the reliability of the indoor lab test results. The test results from both the indoor laboratory test and field test show the same finding where the power consumed by the fan motor marginally increases after the installation of the energy recovery system. The difference observed on the power consumption is only 0.39% higher, indicating that there was only a very small blockage effect experienced with the installation of the VAWT. Further investigation will be conducted on the wind turbine design to further reduce the blockage effect as well as the guide-vane and diffuser design development to improve the VAWT performance.

This designed system is expected to recover 13% of the power consumption by the cooling tower. Meanwhile, it helps to reduce the greenhouse gas emission emitted from the conventional power generation system leading to a healthier life and environment. The value and rating of the building increase because it could be awarded a higher certification in green building index evaluation and the natural turbulence around the buildings which may reduce the efficiency of the VAWTs will also be investigated in the studies. Details theoretical analysis and actual electricity generation measurement will be conducted as well to further examine the reliability of the designed system. The theoretical model and computational fluid dynamics will be validated with the experimental results. For energy generation enhancement, the authors are also improving the energy recovery system from a single rotor to a dual-rotor turbine generator system. The optimum angle of guide vane setting and configuration will be studied as well to further improve the performance of wind turbine. Furthermore, air flow augmentation and re-entrainment effects through diffuser-plates will also be investigated.

Acknowledgments

The authors would like to thank the University of Malaya for the assistance provided in the patent application of this design (Patent No: P2011700168) and the research grant allocated to further develop this design, i.e. University of Malaya High Impact Research Grant (D000022-16001). Sincere gratitude is also dedicated to the Malaysian Ministry of Higher Education (MOHE) for the Prototype Development Research Grant Scheme (PR002-2012A) awarded to this project. Special appreciation is credited to Truwater Cooling Towers Sdn. Bhd. as an industrial partner for providing the testing facilities, fabrication materials and manpower to perform the field tests.

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