Development of the rooftop ventilator powered by photovoltaic energy

Feng-Chyi Duh¹, Tsung-Han Li²
¹ Ta Hwa Institute of Technology
² National Chiao Tung University

Correspondence author email: E-mail : aedfc@thit.edu.tw

Abstract

This study develops a newly rooftop ventilator powered by photovoltaic energy. An experiment is performed to investigate the simulated model’s ventilation performance. Photovoltaic energy were employed to active the rooftop ventilator, three main heat transfer mechanisms enable the indoor temperature to be decreased through the new rooftop ventilator: method 1 is to use the device design produce natural convection, method 2 is to drive fan produce forced thermal convection, and method 3 is to use atomized sprayer absorb heat of vaporization. According to preliminary experimental data results, the maximum effect of decreasing the temperature by natural convection alone was 18.2°C (23.9% temperature drop); when combined with forced convection, the maximum effect was decreased by 24.6°C (44.2% temperature drop). When the forced convection was combined with the endothermic process of evaporative cooling, the maximum effect of decreasing temperature was 15.7°C (31.4% temperature drop). When the device was powered by a self-powered photovoltaic system, experiments showed it greatly improved the indoor air quality.

Keywords: Rooftop ventilator, Natural convection, Forced convection, Evaporative cooling.

1. Introduction

Rooftop ventilation is a highly important element of indoor air quality. Properly inducing ventilation can significantly improve air quality in the metal sheet shelters, while also decreasing reliance on air-conditioning, thus reducing energy consumption. There are a numerous types of rooftop ventilator on the market today. Properly implemented, the ventilator uses the natural forces of thermal effect and wind pressure, referred to as the “Stack effect” to circulate and exhaust the air in the room. Proper ventilation will minimize the temperature differential between the air in the room and the air outside. Simply stated, optimum ventilation will remove heat from the indoor efficiently.

With the elevation of living standard and the strict requirements for the comfortable and cleanliness of our living environment, air conditioner has become an essential device. It has become a need for everyone. Generally, building sector consumes about 30~40% of the world’s energy demand and it is expected to increase gradually in the near future [1]. The high energy consumption of building sector due to the extensive use of air-conditioning is
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quite frustrating. In order to comply with saving energy strategy to implement the government’s energy policy, one of the ventilation strategies that is considerable cheap and technologically simple to operate is the use of wind-driven turbine ventilator. According to the previous work by Lai [2], the installation of the device in building or factory in high outdoor wind condition of 10–30m/s is significantly capable to increase ventilation rate from 60–140m³/h for a turbine ventilator.

However, the performance of wind-driven turbine ventilator is totally depends on the outdoor wind condition, its effectiveness and applicability in erratic is always unstable. Therefore, several studies attempted to research the possibility of combining the turbine ventilator with electrical extractor fan in an effort to improve ventilation performance. This includes the study by Kuo and Lai [3], the study examined the potential of installing a roof turbine ventilator onto a ventilation system serving 14 bathrooms, and assessed its overall ventilation performance. They found that such combination is effective to achieve adequate air change rate in bathrooms. Following this study, Lai [4] conducted a prototype development investigation on hybrid turbine ventilator. The experimental results indicated installing an inner fan at low outdoor wind speed (0 and 5m/s) increased the ventilation rate. On the other hand, the ventilation rate was not improved by installing an inner fan at high outdoor wind speed.

Recently, to lower the energy consumption is a trend in world. For this purpose, several studies proposed to combine the renewable energy, particularly in wind power, solar energy and photovoltaic energy. In the study by Lai [4] showed that the combination of the wind and photovoltaic energy successfully achieved adequate energy for a new common ventilation level. In a more recent study, Ismail and Abdul Rahman [5] indicated that a hybrid turbine ventilator at ceiling level succeeded to reduce indoor temperature and relative humidity of up to 0.7°C and 1.7% relative humidity, respectively. Besides, the different locations of ventilator placement are a highly important element for ventilation performance [6]. To achieve the objective of saving energy, the improvement of energy consumption no longer focuses on the effectiveness of ventilator, scope should be widening to investigate various factors. For example, results from the study of Budaiwi and Al-Homoud [7] showed that acceptable contaminant concentrations during occupied periods could be achieved by different ventilation strategies but at substantially different ventilation energy requirements for a single-zone enclosure. More than 50% reduction in ventilation energy requirements could be obtained while maintaining acceptable indoor air quality if proper ventilation strategy was employed.

A good ventilation system is an effective approach to reduce the dependence of the indoor air quality on the air conditioner. Meanwhile, proper ventilation performance will reduce the energy consumption. Considering the ventilation performance and energy consumption, finding an appropriate ventilator that can secure acceptable indoor air quality with minimum energy consumption is a challenging task in the near future.

The aim of ventilation is to ensure the good characters of the indoor air condition. One of the key issues in the ecological design of the roof annex and containers is the application of renewable energy. In this study, a simulated container model was taken up for experimental test. To reduce the energy consumption, this study proposes to develop a lower energy demand of the rooftop ventilator and energy supply of renewable energy. The design concept in this study is aimed at improving the design of the rooftop ventilator commonly used in Taiwan, and then develop a new rooftop ventilator powered by photovoltaic energy.
2. Experimental facility and method

2.1 Facility description

A new highly functional rooftop ventilator is comprised of individual units: photovoltaic energy unit, forced convection unit, natural convection unit, and evaporative cooling unit, which are installed above the rooftop of the roof annex or container. This study aimed to enhance the ventilation performance using renewable technology, without consuming additional electricity. Therefore, the electricity demands of forced convection unit, natural convection unit, and evaporative cooling unit were met by photovoltaic panels.

The structural diagram of the device in this study, including the various unit systems of the device, is shown in Figure 1; the exploded view of the components for each unit is shown in Figure 2. The device described in this study is to be mainly installed on the roof of iron shacks and container homes. Because the base mask is directly inserted into the roof window and secured by tightening screws to the roof, the device itself and the dissembling process are both extremely convenient.

As showed in Figures 1 and 2, the solar array (#11) of the solar power system (#1) is made from a thin film of amorphous silicon. It is completely paved on top of the solar panel (#12) to absorb sunlight, which serves as the heat emission device for iron shacks and container homes. As the device features of “providing energy whenever there is sunlight”, the solar power system can directly and timely absorb solar energy to convert it into electricity; the cable (#13) connects the solar array to the electric charge controller (#14). The electric charge controller contains an extremely small-loading Schottky diode to prevent the current within the battery (#15) to reversely flow back to the solar array. In other words the design also functions as a protection against overly charge and discharge. The purpose of the temperature controller (#16) is to prevent excessive temperatures inside the room. Therefore when the temperature inside the room reached a specific setting value, the temperature controller will begin to activate the loading operation to dissipate heat.

![Figure 1. Illustrative diagram of the rooftop ventilator proposed in this study](image)

The solar tracking system includes two solar panel racks (#21), a rotation shaft (#22), two photoresistors (#23), connecting wire (#24), electric circuit module (#25), motor (#26), gear (#27) and bearing (#28). The solar panel racks are used to fix the device beneath the solar panel and used to support the solar panel. A hole on the solar panel racks exactly fits for the rotation shaft (#22) to enable the solar panel rotate with the rotation shaft. The
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A circuit module (#25) is the core of the solar tracking system. The primary function of this module is used for detecting. When a photoresistor is used as the sensor, it first detects signals which pass through the voltage follower; the signals further pass through an operation amplifier (OP) comparator and then undergo output processing. Finally, an OP amplifier is used to generate motor-driven signals. The output signals from the main circuit are then sent to the forward/reverse circuit of the motor (#26) to control the motor’s rotational mechanism for the solar panel. In order to enable the solar panel to rotate, the design is similar to a seesaw shape; the sensor (i.e., the photoresistor) is installed on the two ends of the solar panel to be able to detect the sunlight’s intensity. The bearing (#28) of the solar panel center is driven by the motor gear (#27) to operate forward/reverse actions.

The device in this study is installed on the roof window of iron shacks or container homes. The hatchback cover can increase the area for absorbing sunlight and in addition can expand the solar panel’s elevation angle. Furthermore, the size in the horizontal direction of this exterior head cover extends outwards to both ends of the sidewall to form a covering brim, which can prevent rainwater splash into the temperature adjuster and drip inside the room. The outer case system (#3) contains a hatchback head cover (#31) with a symmetrical 12-degree incline design. The purpose of the design is to increase the solar panel’s elevation angle on top of the rack. The sidewalls (#32) of the outer case are all equipped with long and thin air holes to serve as channels for air circulation. These long and thin air holes on the two sidewalls and rear wall enable the emission of hot air from the container home.

The base supporting plate (#33) is designed with three holes, including two fan installation holes (#34) and one sprayer installation hole (#35). These holes are used for installing the fan and sprayer, respectively. The base mask (#36) shape of the base is similar to an upside-down funnel. This design uses the principle of free convection to collect the high-temperature air which rises as it has a smaller density.
This convection-type heat dissipation system is used to remove the heat accumulated inside the room. The core of this convection-type heat dissipation system is based on the two fans (#41) for generating a forced convection effect, which the high-temperature air inside iron shacks or container homes are removed to the outer environment. Another heat dissipation system uses an atomized sprayer (#51) to perform liquid evaporation, a system which absorbs large amounts of heat. When the temperature inside a container home reaches the set value of the temperature controller, the sprayer will promptly spray a suitable amount of coolant from the container. The coolant inside the sprayer’s container is a mixed solution of water and ethanol which can be replenished any time.

Due to the new roof ventilator’s light weight, it dimensions is 540mm (L)×300mm (W)×108mm (H) and can be mounted directly onto any existing roofs with ducting without disturbing the existing structure. Rooftop ventilator fan is driven by photovoltaic energy while the fans and atomized sprayer operate by applying the photovoltaic energy of the sun to decrease indoor temperature by thermal convection and evaporative cooling. The induced air-flow caused by the spinning fans produces a low-pressure region, which pulls the air through the fans. The air drawn out by the rooftop ventilator is replaced by fresh air continuously from outside. Convection would drive the airflow by fans when surrounding is no wind. This could occur in a period of very still weather. To maximize airflow, the fans in the ventilator operated at the rated speed.

Supply end of photovoltaic energy incorporates the photovoltaic panels, wirings, batteries and control panel to provide the power for the fans and atomized sprayer operation. These electrical elements were designed to meet the power requirement of fans and atomized sprayer, and the fans operated at the rated speed proposed by the test result.

2.2 Testing procedures

To verify the expected performance of the device, the experimental model used in this study was based on a closed measurement system to control the environmental status for obtaining reliable experimental data, as shown in Figure 3; the recording and collecting of temperature data was done by a computer. The measurement system was an isolated room that was sealed to completely simulate iron shacks or container homes under sunlight; which was used to predict the expected performance after adding a heat dissipater. All of the materials for constructing the isolated room of the measurement system were of corrugated paper boards for insulation. The paper boards were attached to every side of the isolated room with a thickness of 5mm. The halogen lamp was operated with a power supply to simulate the irradiation from sunlight; the specification of the halogen lamp was 110V and 150W, which each isolated room was installed with 1 lamp. The experiment used a thermocouple and digital hygrometer to collect the temperature from the environment and experimental model. The experiment used a thermocouple and a digital thermometer (record-type four channel thermometer, TM-946), to collect the temperature from the environment and experimental model.

To measure ventilation performance, the indoor and outdoor temperatures need to be considered. The experimental setup of the simulated test is depicted in Figure 2. Initially, only the heat source was switched on. When the indoor temperature of simulated model reached the restricted value (To), the inner fans were turned on to its rated speed, and indoor temperature measurements were performed after the inner fans’ rotation was stable. The same temperature measurement processes were extracted under various testing conditions, consequently when the inner fans reached each stable condition. After completing the final measurement under mixed convection with evaporative cooling, the heat source was switched off.
3. Results and discussion

3.1 Effect of heat dissipation by natural and forced convection

The experiments in this study were divided into two parts. The first part was to explore the heat dissipation by natural and forced convection, where the second part explored the dissipation effect by natural and forced convection with the endothermic process of evaporation. Since the primary mechanism of heat dissipation by forced convection was based on the two fans, the first step in the analysis was taking the type of fan devices (exhaustion and blowing) into consideration. For the data from the first part of the experiment (#1–#5), the first set recorded the changes of temperature in the measurement system in a completely closed status (#1); the second set recorded the changes of temperature in the measurement system with only simple natural convection (#2); the remaining sets applied the two fans for forced convection, in which the third set used both fans for exhaustion (#3), the fourth set used one fan for exhaustion and one fan for blowing (#4), and the fifth set used both fans for blowing (#5). During this first part of the experiment, the maximum temperature by heating was 75°C and experiment time \( t_f = 9000 \text{sec} \). Details of the experimental setting conditions are listed in Table 1.

<table>
<thead>
<tr>
<th>Test No. (#)</th>
<th>Ta, ave (°C)</th>
<th>Fan module</th>
<th>Principles of heat transfer</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>17.1</td>
<td>Enclosed cabin</td>
<td></td>
</tr>
<tr>
<td>#2</td>
<td>17.8</td>
<td>Natural convection</td>
<td></td>
</tr>
<tr>
<td>#3</td>
<td>18.6</td>
<td>2 suction</td>
<td>Natural + forced convection</td>
</tr>
<tr>
<td>#4</td>
<td>17.4</td>
<td>1 suction; 1 blowing</td>
<td>Natural + forced convection</td>
</tr>
<tr>
<td>#5</td>
<td>18.0</td>
<td>2 blowing</td>
<td>Natural + forced convection</td>
</tr>
</tbody>
</table>

Figure 3. The experimental setup of the simulated test
In natural convection, the typical convection coefficient \( h \) has a rather small value about 5~25W/m\(^2\)K. This indicates that the outer temperature should be more sensitive to natural convection. When the calculations were based Newton’s law of cooling, a 1°C increase/decrease of the outer temperature \( (T_a) \) will cause a difference of about 2.5% to heat dissipation by convection. As a result, we rely on the air conditioning system of the laboratory for adjusting the surrounding temperature. From Table 1, the average surrounding temperature \( (T_{a,ave}) \) during the first part of the experiment was from 17.1°C (the lowest) to 18.6°C (the highest).

In the first part of the experiment (#1~#5), the changes of temperature for the measurement system in a completely closed status (#1) was the same as from the previous section. The temperature immediately increased with a rapid rate once the electric heating started; the temperature rise gradually stopped the sharp rise around 420sec after. Based from the data from equation \( (T_t + \Delta t - T_t)/T_t < 1\% \), the temperature in the measurement system was seen as continuously rising until the heating process ended \( (t_f = 9000s) \). When the “solar power roof temperature adjuster” was used as heat exhaustion and to explore the effect of natural convection (#2), it was very apparent that the difference between the two curves gradually enlarged with time. This indicates that the amount of heat dissipated by natural convection gradually increased with the increase of temperature, as in Figure 4. From the curve distribution in Figure 4, it can be seen that the difference between Set #1 and #2 reached maximum at \( t_f = 9000s \), where the maximum temperature difference was 18.2°C.

![Figure 4. Temperature variation in the measurement system (Part 1)](image-url)
We further observed the heat dissipation effect via forced convection. In this part of the experiment, the fans were respectively arranged as both for exhaustion (#3), one for exhaustion and one for blowing (#4), and both for blowing (#5). Furthermore from the curve distribution of Figure 4, the experimental sets of #3–#5 respectively reached the setting temperature (T₀) at 3480 sec, 2430 sec and 1170 sec and started to activate. The temperatures in the measurement system immediately dropped significantly once the fans had activated. As the fans continued to operate with time, the temperatures in the measurement system continuously and steadily decreased. When the end of the experiments were reached (tₕ=9000 sec), the temperatures for experimental sets #3–#5 respectively dropped 24.6°C, 10.1°C and 21.4°C. Results showed that a good effect in heat dissipation was obtained when the fans were arranged as either both exhaustion or blowing. From Figure 5, it can be discovered that the heat dissipation effect by exhaustion was slightly better than blowing. The experiments showed that the maximum temperature lowering effect by natural convection from the first part of the experiment reached 18.2°C, while the maximum dropping of temperature by forced convection can reach 24.6°C; it can be seen that the heat dissipation effect by fan exhaustion was slightly better than blowing.

3.2 Effect of heat dissipation by natural and forced convection combined with endothermic evaporation

In the second part of the experiment, the operation of a sprayer was added to the natural convection and forced convection for measurement and analysis. The experimental condition settings are listed in Table 2. The second column in Table 2 shows the average surrounding temperature (Tₐ,ave) during the experiment which was at 22.2–23.7°C. The maximum difference among all surrounding temperatures was 6.84%, and average fluctuation of the surrounding temperature was Tₐ,ave±3.9%. The third column shows the relative humidity (φ), in which the minimum relative humidity was 55% (#7) and maximum reaching 76% (#6); the fourth column indicates the content of ethanol. The concentrations of ethanol in the experiments were based on volume percentage and prepared in three different concentrations: 10% (#6), 5% (#7–#9), and pure water (#10).
When the setting temperature (To) was set at 50°C, the measurement system began to simulate the situation of sudden temperature rise in iron shacks. The changes of temperature in various conditions are shown in Figure 6 when the effects of natural convection, forced convection and liquid evaporation all existed. It can be seen from the curve distributions that the first three experimental sets (#6~#8) nearly showed no response of temperature decrease. Even when the sprayer respectively began to activate at 1260sec, 1140sec and 1100sec, the high-temperature of 50°C resulted in the measurement system had led to a forced rising air flow caused by natural convection. As a result the misty coolant immediately evaporates when it was sprayed, and the heat absorbed was only of the top region of the measurement system adjacent to the sprayer. Therefore the overall temperature of the measurement system had not been lowered.

In order to overcome the obstacle where the sprayed coolant was unable to carry out its heat dissipation effect, we coordinated the fan with the sprayer in our following experiments. When the sprayer ejects the coolant, the fan was simultaneously activated to blow the misty coolant into the measurement system. The temperature drop phenomenon is significantly seen in Figure 7. The coolant with 5% of ethanol (#9) had a temperature drop effect reaching 14.9°C (29.8% temperature drop); the effect for the coolant with 0% ethanol (#10) reached a temperature lowering effect of 15.7°C (31.4% temperature drop). From the results, the content of ethanol in the cooling liquid did not increase the heat dissipation performance.

<table>
<thead>
<tr>
<th>Test No (♯)</th>
<th>Ta, ave (℃)</th>
<th>φ (%)</th>
<th>Ethanol content (%)</th>
<th>Principles of heat transfer</th>
</tr>
</thead>
<tbody>
<tr>
<td>#6</td>
<td>23.2</td>
<td>73~76</td>
<td>10</td>
<td>Natural convection + endothermic evaporation</td>
</tr>
<tr>
<td>#7</td>
<td>22.2</td>
<td>55~58</td>
<td>5</td>
<td>Natural convection + endothermic evaporation</td>
</tr>
<tr>
<td>#8</td>
<td>22.7</td>
<td>63~67</td>
<td>5</td>
<td>Natural convection + endothermic evaporation</td>
</tr>
<tr>
<td>#9</td>
<td>23.7</td>
<td>72~74</td>
<td>5</td>
<td>Natural + forced convection + endothermic evaporation</td>
</tr>
<tr>
<td>#10</td>
<td>22.3</td>
<td>65~69</td>
<td>0</td>
<td>Natural + forced convection + endothermic evaporation</td>
</tr>
</tbody>
</table>

Figure 6. Temperature variation in the measurement system (Part 2)
We further discussed the effect of relative humidity ($\phi$) towards the experiment results. Relative humidity indicates the ratio of water vapor in the atmosphere to its saturated value when in the atmosphere; in general an environment with lower relative humidity (drier) will have a higher evaporation rate; on the contrary, a higher relative humidity (wetter) will result with a slower evaporation rate. In addition, air with a higher temperature has a higher capacity of holding water vapor. From Table 2, when the relative humidity ($\phi$) for experiment #9 was 72~74%, the average surrounding temperature ($T_{a,ave}$) was 23.7°C; the relative humidity for experiment #10 was 65~69% and having an average surrounding temperature of 22.3°C. The data shows that both the relative humidity and average surrounding temperature for experiment #9 were higher. According to the principle, the evaporation rate for experiment #10 must be slower. Therefore the factor by the surrounding environment caused experiment #9 to have a poor heat dissipation performance.

4. Conclusions

The conclusions derived from the experimental results and analyses of this study are summarized as follow:
(1) The maximum heat dissipation efficiency by natural convection can reach 27.5%; the maximum temperature drop was 17.1°C.
(2) Overall, the maximum temperature drop performance by natural convection was 18.2°C; the maximum effect by forced convection was 24.6°C. Forced convection had a better heat dissipation performance than natural convection.
(3) When considering the heat dissipation effect in forced convection, the performance by fan exhaustion was slightly better than blowing.
(4) The temperature drop effect for the coolant with 5% ethanol was 14.9°C (temperature drop of 29.8%); the temperature drop effect for the coolant with 0% ethanol reached 15.7°C (temperature drop of 31.4%).
(5) The content of ethanol in the cooling liquid did not increase the heat dissipation performance.

The experimental results indicate installing a photovoltaic energy unit can afford the system power sufficiently. The indoor temperature was improved by installing two fans at rating speed and an atomized sprayer. In combination the operation of fans and atomized sprayer simultaneously is highly recommended to achieve...
excellent ventilation performance. Photovoltaic energy is employed to activate the rooftop ventilator, saving energy that would otherwise be consumed by air-conditioning in the container or roof annex. Therefore, this rooftop ventilator design alternative is a promising means of improving the indoor thermal comfort in container or roof annex.

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Reference