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Development of a wind forced chiller and its efficiency analysis

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ABSTRACT

Until now, the technical development of wind force is mainly combined with electrical generator and already achieves the skillful technique in application. In this paper the newly developed windchiller directly applies the mechanical energy of wind force for refrigeration instead of the traditional electrical/mechanical energy conversion. The devise avoids energy loss during the two to-and-fro energy conversion processes between wind force and electrical energy. The special finished wind machine applies the technique with two directions to capture the wind force, the faced and its opposite directions, in the fans design. Between the wind turbine and the compressor, a transmission system with a fixed conversion rate 1:20 was used for acceleration. After the combination with open-type reciprocating compressor, the wind forced chiller is built. The windchiller increases the working efficiency in comparison with the refrigerating system of indirect connection from wind generator to refrigerator and ignores the unstable property of wind force. The strength of wind force influences only the windchiller's efficiency; the stronger wind force, the larger windchiller's efficiency. The experimental results show the newly developed windchiller's efficiency ca. 21.28%, which agrees to the pre-evaluation and achieves a high efficiency.

1. Introduction

The earth energies consumption overly in the 21st century accelerates the extremely serious energy crisis and environmental pollution. To retard the global environmental deterioration, the developments and applications of renewable energies are of great urgency. Although the finding of a new fuel to replace the petroleum can solve the energy crisis effectively, the exhausting wastage of petrifaction fuel usually causes the environmental pollution. This is the reason why the energy crisis and the environmental pollution come always the correlative consideration together for solution. Therefore, a new and clean energy for replacement of the ready exhausted petroleum is the immediate solution.

The green energies are the best alternative energies, which consist of the solar, wind, bio-energies, and so on. Green energy is the general designation of renewable and pollution-free energies, which are normally yielded by the natural phenomena. It is clear that the development of green energy is the best way to solve the two previous problems. Within all green energies, the applications of wind force and solar energy are the two most skillful technologies today. The development of wind force is relatively lower than that of solar energy at price and technique. Some highly developed countries, e.g.

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Fig. 1. Schematic analysis of efficiency for a wind power generator.

Germany, Denmark, and USA are working toward the development of wind energy as an important direction of growing green energy. Until now, the technical development of wind force is combined with electrical generator and had already achieved the skillful technique in application [1,2].

Applications of draw water, grind corn, etc., with wind machine using wind force can be said as an age-old technology. Presently, people prefer and have got habituated to use the electrical products due to the popular and advantageous electrical utilities. The growing wind energy almost focuses on the conversion from mechanical to electrical energy. This conversion technique often causes large energy loss during the transformation between mechanical and electrical energies. A maximum reachable working efficiency of a wind generator is about 20–40%. Fig. 1 shows the schematic analysis of efficiency for a wind power generator, where P_W is the input wind power, P_E is the output electrical power, and η_W, η_T, η_G are the coefficients of efficiency for wind turbine, transmission, and generator individually.

According to Fig. 1, the output electrical power (P_E) is written as

$$P_E = P_W \cdot \eta_W \cdot \eta_T \cdot \eta_G \tag{1}$$

where $\eta_W \leqslant 0.59$ is known as the Betz limit or Betz' law, η_T can reach upon 95%, and η_G is normally 50–80%. Certainly, for a good and special devoted generator, η_G can reach larger than 80%. [3] For better working efficiency and conserving energy topics, the suited functional products will be set as researching and developing topics. The age-old applications of wind force applied mechanical energy directly for pumping, grinding, and so on. A suited functional product, e.g. wind forced chiller, will better apply mechanical power directly for working. This will reduce the transformed wastage between mechanical and electrical energies [4,5].

Developing a wind forced chiller, which uses the mechanical energy of wind force directly for refrigeration instead of the electrical energy converted by the mechanical energy, is a new idea. It avoids energy wastage during the energy conversion processes between wind force and electrical power. Moreover, it develops a new usage of wind force, which is renewable and green energy. The wind forced chiller ignores the unstable properties of wind using the technique of energy storage refrigerator. The efficiency of energy storage refrigerator depends on the unstable wind force in realtime which can reduce the influent variables of the research. The wind force is the main and only parameter to influence the investigation. The wind forced chiller is aimed to develop for tall buildings upon the housetop and the place along the coast, where the wind force is much stronger. The wind forced chiller can reduce the depletion of electrical energy on the summer and the cost of ice factory along the coast [6–8].

2. Efficiency analysis

In comparison to the traditional closing system of refrigerator which can achieve a maximum working efficiency with ca. 40% and be driven by a wind generator with ca. 20% efficiency, the wind forced chiller should have the higher efficiency than it. Fig. 2 shows the schematic illustration to describe the efficiency of wind forced chiller in comparison with wind generator driven traditional refrigerating as well as air-conditioning systems. A wind generator captures normally ca. 20–40% wind energy. The value is combined with the maximum efficiency of a closing refrigerating system and receives a ca. 8% final efficiency through two to-and-fro energy conversion processes. A wind forced chiller jumps the two conversion processes and directly applies the mechanical energy of wind force [9].

About the efficiency analysis, the effective mass flow rate of wind ($\dot{m}$) is first considered. Eq. (2) shows the effective mass flow rate of wind for wind machine, where A is the vane sweeping area of wind machine, ρ is density of the air, v is the wind mean velocity, and t is the working duration

$$\dot{m} = \frac{\mathrm{d}m}{\mathrm{d}t} = \rho A \frac{\mathrm{d}x}{\mathrm{d}t} = \rho A v \tag{2}$$

$$\mathrm{d}m = \rho A v\, \mathrm{d}t \tag{3}$$

$$m = \rho A v t \tag{4}$$

A combination of Eqs. (2) and (5) results in the kinetic energy of wind (E) as Eq. (7)

$$E = \frac{1}{2} m v^2 \tag{5}$$

$$= \frac{1}{2} (\rho A v t) v^2 \tag{6}$$

$$= \frac{1}{2} \rho A v^3 t \tag{7}$$

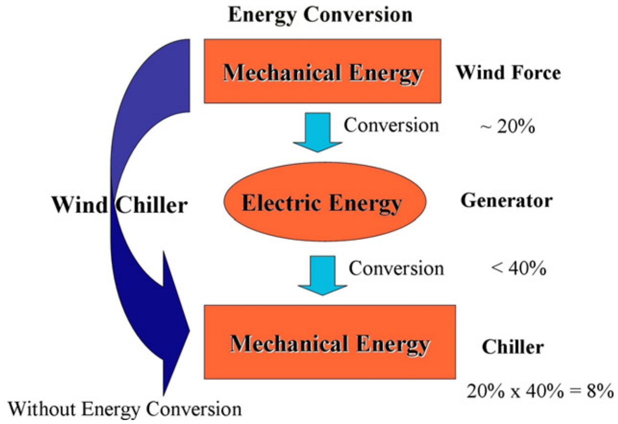

Fig. 2. Schematic illustration for the theoretical comparison of energy conversion between wind generator driven traditional refrigerator and wind forced chiller.

The received kinetic energy is converted to heat (Q) by the wind forced chiller and cools the water in the ice pail. Eq. (8) displays the relationship of heat capacity of water in the ice pail, where M is the mass of water, s is the specific heat, and ΔT is the change of water temperature

$$Q = Ms\Delta T \tag{8}$$

During measurements, the heat capacity of water in the ice pail will be transferred into the air through the natural heat convection, because the used ice pail was open and without any heat insulation. The lost energy (H) during natural heat convection between water and air can be represented as

$$H = Ms\Delta T \tag{9}$$

Experiments used calibration technique to estimate the lost energy of water in ice pail during natural heat convection, where the calibration curves are plotted with the data of the water temperature change vs. the measured time. Two ice pails are individually with and non-heat insulation filled the same quantity of water. By comparing the lost energy between heat insulation and non-heat insulation ice pails in the same duration (D), the so-called technical lost energy (ΔH) is obtained as follows, which should be considered as an effective energy

$$\Delta H = Ms \cdot D(S_1 - S_2) \tag{10}$$

where D is the measured duration, S_1 is the slope of the fitting curve in the non-heat insulation ice pail and S_2 is slope of the fitting curve in the heat insulation ice pail of calibration curves. The product of D and S_1 is the total energy loss using the non-heat insulation ice pail, whereas the product of D and S_2 is the normal energy loss using the heat insulation ice pail.

The efficiency (η) of wind forced chiller can be calculated by using the following relationship in Eq. (12), where the input energy indicates only the kinetic energy of wind by ignoring the influence of wind inner energy

$$\eta = \frac{\text{Output Energy} + \text{Technical Lost Energy}}{\text{Input Energy}} \times 100\% \tag{11}$$

$$= \frac{Q + \Delta H}{E} \times 100\% \tag{12}$$

3. Experimental details

Realizing the conception of wind forced chiller needs some experimental data for the evaluation of feasibility and efficiency. The required experimental data should be, e.g. the torque of wind machine, the starting torque of compressor, the relationship between wind force and torque of wind machine, and so on. For these purposes, the experimental setup has to be designed as the combination of wind machine and refrigerator. The finished experimental setup includes two parts, the wind machine and the refrigerator. The two parts are combined together and the finished instrument is set up upon the housetop of the 11th floor building which is about 40 m high. Its place is at the National Taipei University of Technology. The workable time at the place is about one hundred days per year. The wind machine and the refrigerator will be detailed as follows.

The applied wind machine is newly developed in the laboratory which is especially considered on the tall buildings. Fig. 3 shows the photo of the wind machine, where the right and top sign of CCT is a mark of the work group.

The wind machine consists of five main parts which are the wind vane system, the rotation axis, the transmissions system, the trestles, and the turnable trestle. The wind vane system is built with eight vanes which are individually 1.65 m long

Fig. 3. Photo of the wind machine with finished setup.

and 30 cm wide. The wind fan has a two-layer structure where every layer consists of four vanes. Fig. 4 shows the schema of the wind vanes where the schema of vanes with dash line marked is the second layer structure. The vanes are fixed on two quadrilateral vane stages with vertical formation on each other (see Fig. 4).

The finished wind vane system is fixed on the rotation axis with two bearing fulcrums. A gear is built on the axis of the fan between the two bearing fulcrums for transmission requirement. The complete wind fan system is sustained by the four boxes trestles and the trestles are designed for assembly. The turnable trestle consists of two round plates and is set up on the ground for the wind machine to turn the direction which is in order to match the wind direction manually. The under plate is fixed on the ground and the upper plate is turnable [10]. Table 1 shows the components of the wind machine.

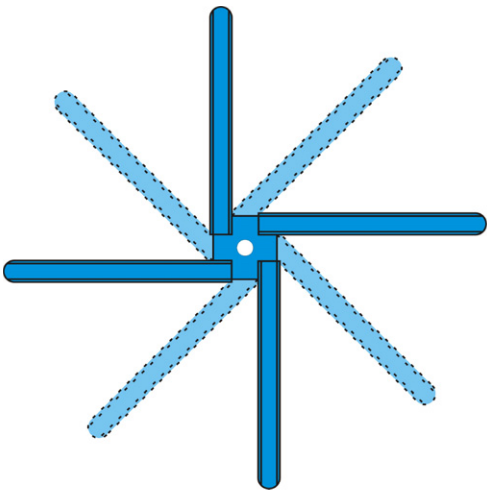

Fig. 4. Schema of the wind vanes.

Table 1
The components of the wind machine with size and quantity

Components	Size	Quantity
Vane	1.65×0.3 m^2	8
Vane stage	47×47 cm^2	2
Trestle	$60 \times 60 \times 60$ cm^3	4
Under round plate	$\phi = 1.1$ m	1
Upper round plate	$\phi = 0.9$ m	1

A transmission system with fixed conversion rate 1:20 was built in the windchiller to accelerate the compressor, where the conversion rate from the axis of the fan to the gearbox is 1:4 and the gearbox is 1:5. Fig. 5 shows the three-dimensional description of the transmission system. The connection between the gearbox and the axis of the fan uses gear and chain system, whereas the connection between the gearbox and the compressor uses belt system.

Fig. 6 shows the schematic descriptions of the transmission system. The optimal and effective working speed of the applied compressor is ca. 1000–1500 rpm, which is accelerated by the transmission system. In the accelerating procedure before reaching the workable rotational speed of the compressor, a clutch is used for reducing the drag force of the compressor. The compressor works only when the rotational speed reaches the effective working speed.

The wind machine is specially suited for the tall buildings in city. Due to the 100% security requirement in the city and upon the tall buildings, the wind machine is designed as the fixing model. According to a long-time measurement, the average flow direction at the testing place shows a nearly fixed mutual direction which gives the simple setup of the wind machine. The wind machine is fixed on the direction and turns with the special designed vane which can turn in two directions. Fig. 7 illustrates the design of the vane, which turns with mutual wind. Certainly, this wind machine is designed for big torque utilities and its rotational speed should be slow.

The refrigerator of the windchiller uses simply the traditional cooling system from automobile air condition and is designed as an energy storage system. The specialization of the cooling system uses the reciprocating compressor which is independent on the rotational direction. This means that the compressor works with the prograde and the reverse rotational directions. The reciprocating compressor is better and easy to combine with wind machine due to its two workable rotational directions [11]. This work developed a windchiller which directly uses the mechanical energy for cooling system. A starting torque of the applied compressor is measured, and it received a value of 0.68 N m.

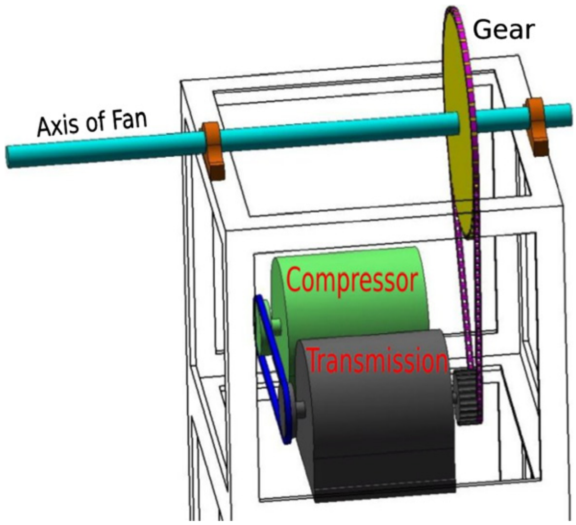

Fig. 5. Three-dimensional description of the transmission system.

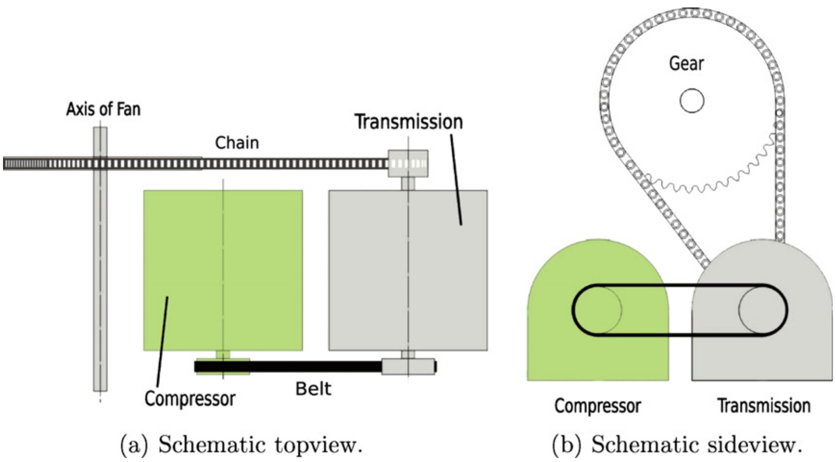

Fig. 6. Schematic descriptions of the transmission system.

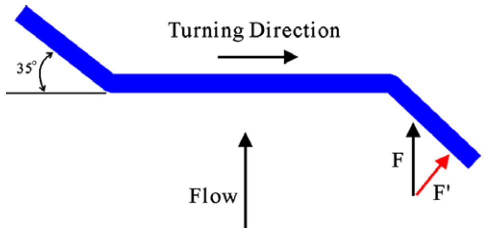

Fig. 7. Schema of the wind vane for two turnable directions.

4. Results and discussion

Experimental results and discussion for this paper are focused on the feasibility and efficiency of the newly developed wind forced chiller. Fig. 8 shows the measured working wind speed of the wind forced chiller in comparison with the average wind speed in Taiwan. The black dick dash horizontal line indicates that the average wind speed in Taiwan is around 4 m/s. Fig. 8 illustrates that the starting wind speed of the wind forced chiller is ca. 3 m/s, which is slower than the average wind speed in Taiwan. This means that the newly built wind forced chiller can work in the average wind speed in Taiwan. On the other hand, the analysis of feasibility of the wind forced chiller in Taiwan is successful.

The wind forced chiller cools the water in the ice pail discontinuously due to the unstable wind phenomenon. The cooling process is discrete and the created energy was saved into the water in the ice pail. In the experiments, the applied ice pail is

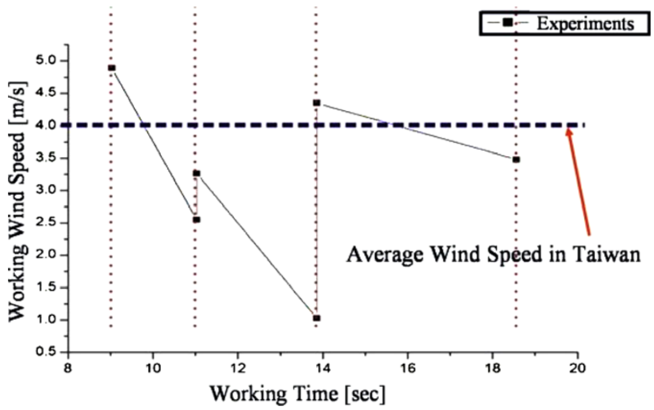

Fig. 8. Analysis of feasibility for wind forced chiller in Taiwan using the results of the comparison with the starting wind speed.

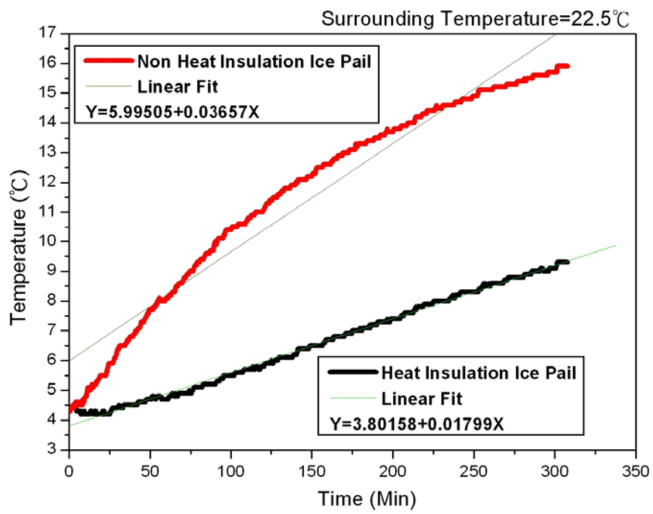

Fig. 9. The calibration measurements for the lost energy during the natural heat convection between water and air.

open and without any heat insulation. This caused the in-water saved energy to lose into the surroundings through the natural heat convection between water and air all the time. The natural heat convection between water and air can be reduced by using thermal insulated ice pail or the technical lost energy (ΔH) through the natural heat convection should be considered as effective work. This means that the technical lost energy should be added to the final efficiency analysis. Fig. 9 shows the calibration measurements for the natural heat convection between air and water in the ice pail with heat insulation and non-heat insulation systems.

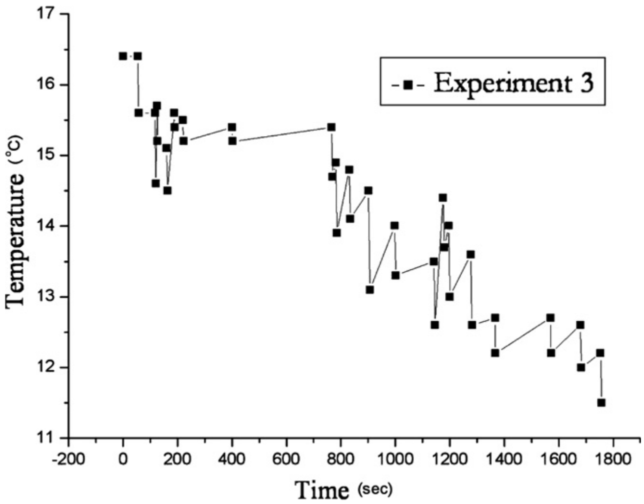

Fig. 10. Relationship between the water temperature in ice pail and the working time of the wind forced chiller.

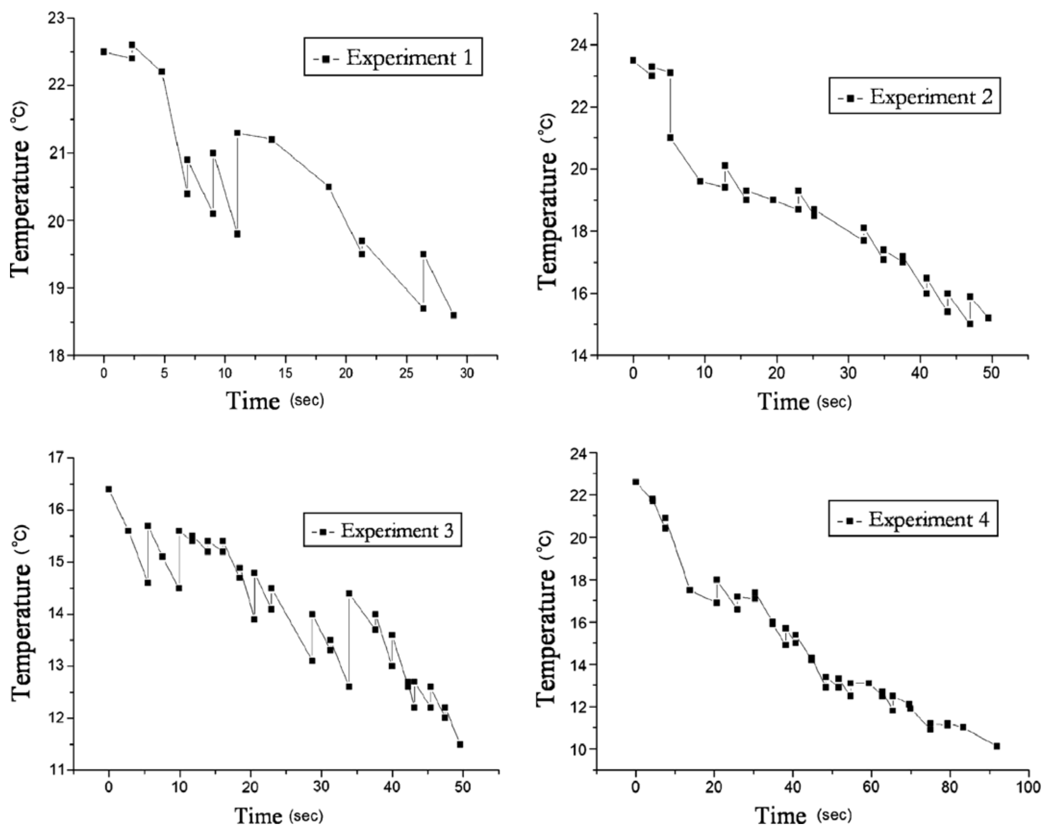

Fig. 11. The relationship between the water temperature and the working time of the wind forced chiller with different measuring conditions.

Table 2
Summation of efficiency with technical lost energy during the natural heat convection of water 13.98 kJ

No.	Input (kJ)	Output (kJ)	Efficiency (%)
1	650	201	33.07
2	2029	281	14.54
3	1322	351	27.61
4	4732	454	9.89
Average			21.28

According to Eq. (9), the lost energy difference between ice pails with heat insulation and non-heat insulation systems is ca. 13.98 kJ in 30 min, which is called here as the technical lost energy during the natural heat convection and will be added to the effective work by calculating the working efficiency

$$\Delta H = 6\ \text{kg} \cdot 1\ \text{kcal/kg}\ ^\circ\text{C} \cdot 30\ \text{min} \cdot (0.03657 - 0.01799)\ ^\circ\text{C/min} \quad (13)$$
$$= 3.34\ \text{kcal} \quad (14)$$
$$= 13.98\ \text{kJ} \quad (15)$$

Fig. 10 shows the water temperature variation in ice pail vs. the working time of the wind forced chiller. The total measured duration is 30 min. Fig. 10 exhibits that the water temperature varied from ca. 16.5 °C to ca. 11.5 °C, and in the measured duration the water was cooled while the windchiller was working effectively. Moreover, the happened sections of increased temperature shown in Fig. 10 are without the operation of windchiller and the natural heat convection between water and air carried heat energy off.

Fig. 11 shows four experiments and displays only the effective working time of the wind forced chiller. The time without the effective operation disappears as shown in the figures. Their total measured time is 120 min and every experiment occupies 30 min. Table 2 exhibits the summation and the average of the four measurements. In comparison to experiment 1 with experiment 3 shows clearly that cooling in the lower temperature of water obtains lower efficiency. The result agrees to the normal refrigerating system. The cooling operation at lower temperature situation has also larger energy wastage. This agrees also to the results of experiment 2 and experiment 4. The efficiency of experiment 4 is smaller than experiment 2 due to the lower water temperature in experiment 4. Table 2 indicates the average efficiency ca. 21.28%.

5. Conclusions

This paper has successfully performed the design, the building, the evaluation of feasibility, and the measurements as well as the discussions of efficiency for the newly developed wind forced chiller. The combination between wind machine and chiller for the wind forced chiller is successfully built in this work. The applied wind machine is with eight vanes and every vane is 18 kg. A starting torque of the applied compressor is measured, and it received a value of 0.68 N m, which determines the feasibility of the windchiller. The used transmission system is with the conversion rate of 1:20. The feasibility of the windchiller in Taiwan is evaluated and receives a positive answer, which is also suitable for use in the other locations with the wind speed larger than 3 m/s. The system's working efficiency for this wind forced chiller with four experiments achieves a value of 21.28%.

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