International Journal of Thermofluid Science and Technology (2021)
Volume 8, Issue 2, Paper No. 080201
https://doi.org/10.36963/IJTST.2021080201
Research Article

Investigation of optimization of solar energy refrigerator with natural humidifier

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Received: 15 December 2020; Received in revised form: 12 March 2021; Accepted: 20 March 2021; Published online 03 April 2021

Abstract

Cold chain processes of horticultural products in tropical countries is very urgent to maintain product quality. In Indonesia, the temperature and humidity are relatively high, so that the deterioration of horticultural products is very fast. Because of the high humidity, this condition can highly possibly use a natural humidifier for a cold room by purging humid ambient air to the refrigerator cabin with the best certain time. Meanwhile, as a tropical country, solar energy has good reliability to be developed. This study aims to determine the performance of the medium temperature refrigerator with a natural humidifier using solar energy as energy source. This research was conducted as an experimental investigation. The rig has been built completely with measurements and instrumentation for precise temperature and humidity control. The results showed that the system reached a quite good coefficient of performance (COP), with the thermodynamically COP of 3.6. However, humidifiers contribute a cooling load which can affect the temperature increase of 1^{o} C - 1.5^{o} C in the cooling system. Further studies will examine the optimization of the refrigerator system with natural humidifiers with low electricity consumption and eco-operating conditions with the best combination of temperature and humidity to keep the product of good quality in a long storage time.

Keywords: Natural humidifier; Medium temperature refrigerator; Solar energy; Eco-operation.

1. Introduction

Post-harvest storage of vegetable and fruit products is very important because it is very susceptible to the rate of decay caused by biochemical processes and microorganisms [1]. Temperature plays an important role in reducing the rate of product deterioration. Horticultural products have a certain temperature and humidity in storage, where each product requires different conditions. However, in general, storage of fresh vegetables and

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fruit ranges from 0^oC to 15 ^oC with relative humidity ranging from 80% to 95% and post-harvest can be maintained for 3 to 6 weeks. Meanwhile, some Indonesian horticultural products such as durian, mangosteen, and chili require an average temperature of 10^oC-15^oC with a relative humidity of 80% -95% for a storage period of 2 weeks to 1 month and of course the storage can take longer, if it is set at a lower temperature [2]. The food industry, which used to preserve fresh produce at temperatures above 0^oC, has now lowered it to -18^oC. It aims to reduce the level of physical, chemical and microbiological damage [3]. The quality of post-harvest horticultural products is maintained by a system of reducing temperature and maintaining humidity. It is known that maintaining moisture can increase the resilience of fresh fruit and vegetable products and can maintain product quality (texture, nutrition, aroma and taste) and it was found that the delay in post-harvest cooling time will degrade the quality quickly [4,5].

The development of refrigerator systems is focusing on using natural working fluids that are environmentally friendly and efficient. For example, Carbon dioxide is excellent alternative refrigerant because of cheap, negligible Global Warming Potential (GWP) and zero Ozone Depletion Potential (ODP). However, it still requires more serious solutions in terms of safety issues and low coefficient of performance (COP), when it applied in a tropical environment [6,7]. For refrigerator applications, other natural working fluids, such as R600a are already widely used, since the R600a also has a very low GWP. In future, a new refrigerator concept will be developed according to environmentally friendly concept and of course, it should high COP [8].

Product quality can be maintained by ensuring control precision of temperature and humidity [9]. Hung et al. [10] more concerned to design a humidifier that produces very small diameter humidifying particles to increase the quality of the product. This is intended to keep the product fresh and to avoid an increase in the growth of rotting microorganisms due to high humidity. With this method, it is also possible to maintain high humidity while maintaining the wet level of the product, to control the freshness of the product by reducing the development or activity of microorganisms. Besides, control of temperature humidity by the combination of percentages amount of purging fresh air play important thing to increase the efficiency of the system [11] and Chineye et al. [12] provides active natural evaporation which can save energy up to 30% but only works at 23^oC which is used for temporary storage of horticultural products (pre-cooling) in agricultural areas.

The feasibility of using solar power as an energy source in the refrigerator system has been studied in various countries similar to the condition of Indonesia. Modi et al. [13] conducted a study on the use of solar power for conventional refrigerator systems. The system was redesigned with the addition of batteries, inverters, and transformers with photovoltaic energy sources. The results showed that the performance (COP) of the refrigerator decreased from morning to evening, with a maximum COP of 2.1 at 7 am and economically it still requires quite high investment costs because the battery price is still relatively expensive. Bilgili [14] researched by making solar electric-vapor compression refrigeration (SEVCR) system, this system is very suitable for cooling during the day. Gupta et al [15] conducted research on the development of stand-alone solar panels as an energy source for the refrigerator system, and analyzed the appropriate solar panel design for a particular refrigerator capacity, and found that solar power was particularly suitable for the refrigerator system. Daffallah [16] investigating an energy-efficient approach to providing cooling needs is one of the challenges facing most developing countries. This study was conducted to assess the performance of the DC 12 V and 24 V photovoltaic refrigerators

with/without loading which were operated at 25 ℃ and 35 ℃. Experiments were carried out at different thermostat settings in the refrigerator. Daily compressor running time and refrigerator energy consumption are calculated under various operating conditions. Monthly and yearly refrigerator consumption is also carried out. Minimum and maximum increase in compressor operating time per day for each increased degree (average from 25^oC to 35 ℃) in ambient temperature.
The operating ratio of a 12 V DC refrigerator is much more efficient than a 24 V operation, especially at higher ambient temperatures with an average energy saving of 81.28 kWh / year. The performance of the refrigerator system is compared to the solar power system of a conventional electrical system by adding a battery, inverter and transformer. The performance coefficient (COP) was observed to decrease with time from morning to evening and a maximum COP of 2.102 was observed at 7 am. As a COP the fridge is pretty good. From an economic point of view, this can only be economically viable considering carbon trading options, and initial subsidies or reduced component costs - particularly photovoltaic panels and battery banks. The RET Screen simulation shows that the system cannot survive economically without initial financial incentives or Government subsidies, or a substantial reduction in the cost of the more expensive components. A minimum initial subsidy of 15% is required to bring the financial repayment period of the current system to an assumed project life of 24 years. Furthermore, to return the repayment term back to an attractive figure, the subsidy is at least 70%. [17]. Temperature control in household refrigerators to environmental and economic plans is very important. Refrigerator energy consumption is greatly influenced by room temperature, door opening and thermostat settings. A household refrigerator powered by photovoltaic energy is tested in a laboratory to determine the effect of thermal regulation on energy consumption. Energy optimization reduces aggressive methods of electricity production. Energy efficiency and solar energy present important alternatives in three areas of energy, economy and environment.

The reduction in energy consumption allows a reduction in the capacity of the PV generator and solar battery. This optimization reduces the cost of autonomous PV installation and helps generalize renewable energy in the domestic refrigeration sector [18]. Refrigerators with AC current are associated with relatively high-power consumption and power spikes compared to refrigerators with DC current. The economic assessment carried out between an AC refrigerator (with inverter) and a developed DC refrigerator (without inverter) both powered by a solar/photovoltaic electric system indicates that a DC refrigerator has the potential to reduce overall system installation costs by 18% as compared to a cabinet ice air conditioner. For stand-alone cooling using a solar PV system as an energy source, it is more economical to use a DC refrigerator instead of an AC refrigerator [19].

Simulation of a solar vapor compression refrigeration system with a variable speed compressor in real weather conditions using data sheets (PV panel and compressor) available from the manufacturer. Compressor operating speed is determined to model the variation in the performance of the refrigeration system per hour. The analysis and simulation results show that the COP of the refrigeration cycle for the selected day is around 2.25 when the compressor is running at low speed, and the COP drops to the lowest value of 1.85 when the compressor operates at the highest speed. Furthermore, the simulation results show that an estimated radiation intensity of 315 W / m^2 must be received at the tilt panel to run the compressor with a minimum rotating speed of 1800 rpm. To drive the compressor at its maximum rotating speed (4200 rpm), an estimated radiation intensity of 700 W / m^2 is required to fall on the PV panel. Finally, the proposed method can be used to estimate the performance of a solar PV cooling system in direct combination with a variable speed compressor under certain weather conditions [20]. The photovoltaic variable speed direct current (DC) cooling system of the photovoltaic (PV) cell is directly connected to the compressor without battery and inverter, and the speed of the DC compressor changes with the radiation intensity. Compared to the fixed speed mode, the cooling capacity of the variable speed mode increased by 32.76% and the average PV utilization efficiency increased by 45.69%. As ambient temperature increases, the average cooling capacity decreases significantly, but the increase in mean power consumption is not seen, which indicates that ambient temperature has a greater influence on cooling capacity and has less effect on power consumption. Radiation intensity has a significant effect on system performance. As the radiation intensity increases, the cooling capacity increases significantly [21].

Therefore, to improve the performance refrigerator system, several optimization strategies are recommended. Depend on previous studies, it can be summarized that energy from photovoltaics is sustained when applying to conventional refrigeration systems. and also humidity plays an important role to improve the quality of the product to be stored.

2. Experimental setup

To get an optimization between the solar energy source that is applied in the tropics with the optimization of the performance of the refrigeration system, two main test rigs were built in this study. First, the equipment is a prototype of a medium temperature refrigerator with AC electricity consumption. The refrigerant used is an environmentally friendly (hydrocarbon) type R600A. Prototype refrigerator is a vapor compression cycle system with the main components of compressor, plate evaporator with a blower, condenser, and capillary tube. The prototype is equipped with a natural humidifier to keep humidity when the room temperature decreases below the dew point. This humidifier system is very precision-controlled as shown in Fig. 1.

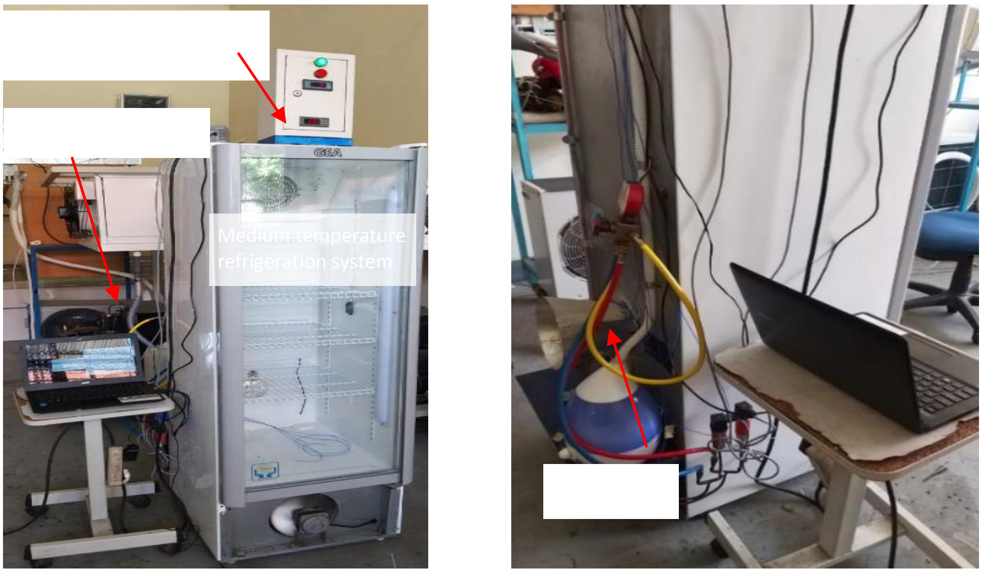


Fig. 1. Medium temperature refrigerator test rig.

The data logger has been prepared for temperature, humidity, and pressure measurement. The probe uses a K type thermocouple and pressure transducer with a voltage signal. The high-pressure and low-pressure lines are measured using pressure transducers connected to a data logger. Environmental conditions are measured using a special logger which includes air temperature, humidity, and dew point. Data is recorded every 2 seconds. The thermocouple has an accuracy of +/- 0.5K, humidity +/- 0.5%, and a pressure (voltage output) of 0.08%. The prototype refrigerator was redesigned to meet the medium temperature conditions specified standard storage for fruit and vegetables (ASHRAE standard) with temperatures of 0^oC and 5^oC, and humidity-controlled at 90%.

The photovoltaic array system consists of a photovoltaic array, Solar Charge Controller (SCC), Inverters, battery with a capacity adjusted to the capacity of the refrigerator system. The solar power system is shown in Fig. 2.

Fig. 2. Photovoltaic array test rig.

The array capacity is 600 Wp with 1000 W inverter, maximum SCC 30 A and 200 Ah battery. This solar power system drives the refrigerator system during the daytime, and automatically switch change to the national grid at night using an automatic switch changed control system.

2.1 Experimental procedures

The prototype medium temperature refrigerator has been modified to meet operating minimum temperatures at 0^oC and humidity of 95%. Humidifiers are designed to use controls using a timer that is turned on for 5 minutes in every 30 minutes in order to purge humid fresh air to the cooling room (cabin). The temperature has been set in the refrigeration system depend on the temperature in the cabin. The measurement position for refrigeration cycle is shown in Fig.3. Thermodynamically in the vapor compression system point 6 - 1 is the compression process with temperature and pressure measurement. Points 2 - 3 are measured for temperature and are assumed to be constant pressure similar point 1, point 3 - 4 is iso enthalpy - expansion process with and temperature and pressure are measured, Points 4 - 5 are evaporation with an assumption of constant pressure and points 5 - 6 are superheating processes where temperature is measured.

The experimental test covered two groups. The first testing was the photovoltaic test. The current and voltage in each part of the photovoltaic is measured under daily sunlight irradiation from 8.30 am to 4.30 pm at local time. Secondly, the refrigeration test was carried out with the temperature set at 0^oC and 5^oC (below than standard temperature of the requirements of the product) to get longer storage and better quality of the products. The humidity at the cabin set at 90% RH. Humidifier operational effect toward increasing temperature is measured at point 6 (T_6). Testing was carried out with the actual products (vegetables). Also, testing observes the performance of the refrigeration system can keeps the quality of the product after being stored in the refrigerator for a certain time.

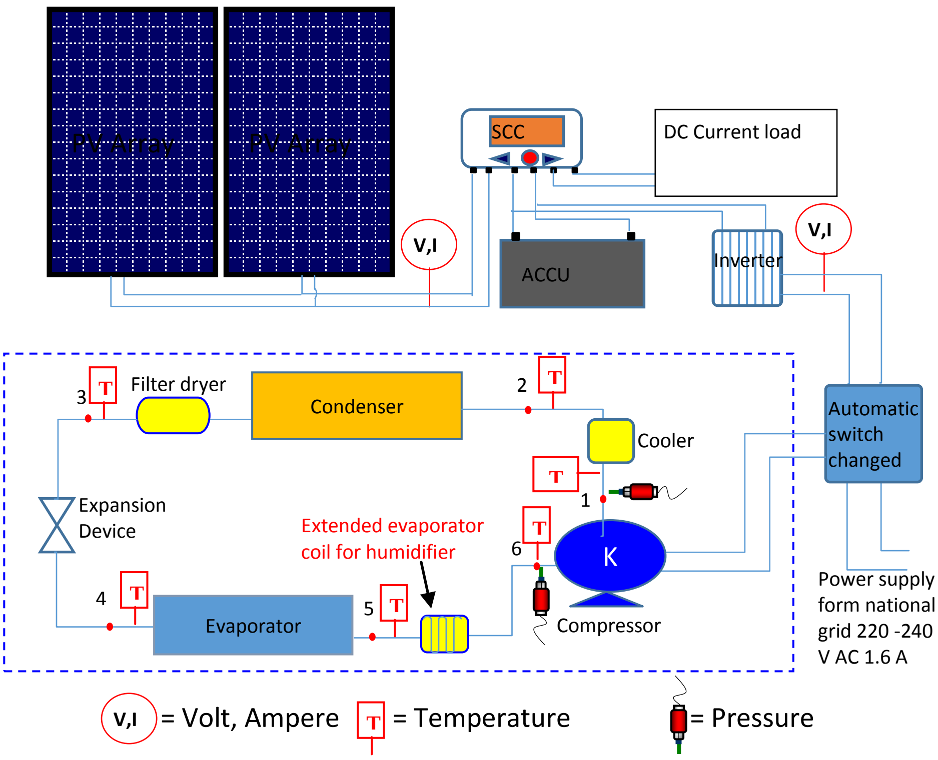


Fig. 3. Schematic diagram of experimental rig and measurement positions.

2.2 Data acquisition and analysis

The system refrigerator data is logged every 2 minutes and stored on the personal computer (PC). All experimental data is imported into spreadsheets to make it easier to calculate and analyze using simple statistical methods. Data are tabulated in tables and graphs. The calculation of the performance coefficient (COP) of the system uses the @Cool pack computer program. Analysis depending on the respective temperature settings with product load. Solar energy analysis using references from the @PVSys software.

3. Results and Discussion

In this study, experimental data acquisition covering data of photovoltaic power supply characteristics. The operational analysis of the natural humidifier was also investigated in-depth, in fact when the humidifier operated where purging ambient air to the cabin that will be as a cooling load for the system. So, there are energy losses that occur in this process, however, it can be investigated to get fewer energy losses. The main data is the performance data of the refrigeration system. Finally, product quality is analyzed visually after being stored for a certain period.

3.1 Photovoltaic energy supply and ambient condition

In this preliminary result, detailed data on the output of solar power that can be consumed by the refrigeration system. The solar power in this experiment takes photovoltaic data out to get the optimum voltage and current according to the direction and tilt angle of the solar panel. The data is summarized in all facing directions (East, North, West, and South) and the angles 0^o, 15^o, 30^o, and 45^o at Bali State Polytechnic-Bali Indonesia. Current (I) according to the facing and angle is shown in the following Fig. 4.

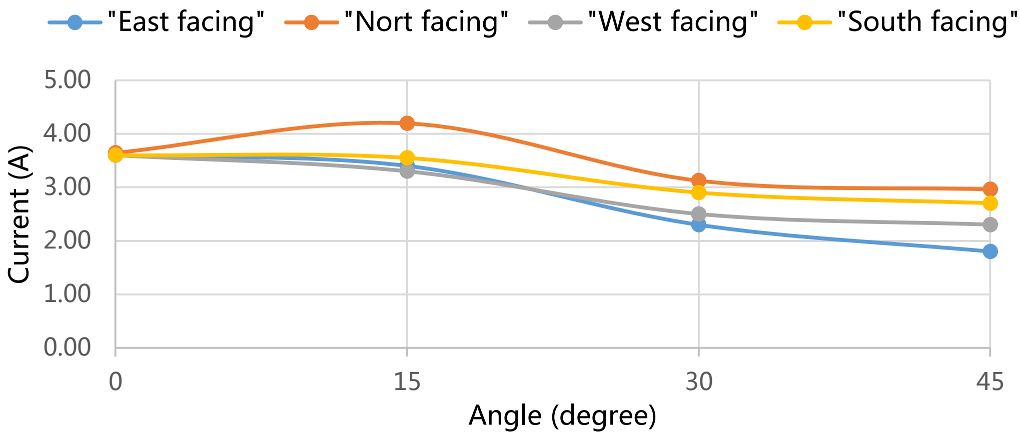


Fig. 4. Variation of current (I) with combination of facing and angles.

Fig. 4 shows the results of the data in terms of facing and angle that can produce a maximal current which is facing to the north with an angle of 15 degree, so that further data trends show the current output from the photovoltaic along with the shining sun from 8.30 am to 4.30 pm (local time) as shown in Fig. 5.

Current (A) output from photovoltaic show naturally varied according to solar irradiation trend at whole day. The current output is excellent at 12.00 until 13.00 (at local time) and still getting solar power for eight hours a day. With this condition, the photovoltaic system could drive the refrigerator during the daytime for 12 hours which is supported by batteries. At night time, the power-driven is switch on national grid electricity. So, the electric power supply for the refrigerator was stable in all the operating time.

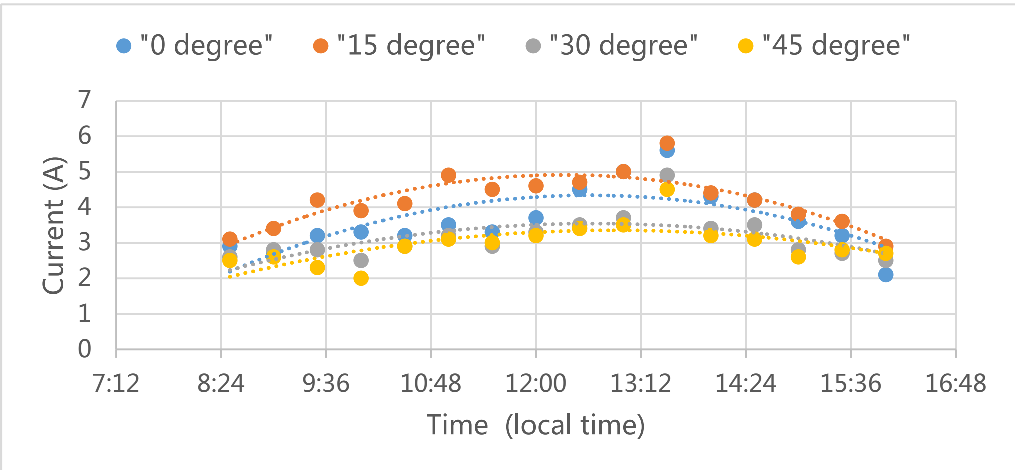


Fig. 5. Variation current output during a day (facing North).

In addition, ambient and humidity condition data has been obtained that average daily environment temperature is 81.4 F or approximately 28.4 ^{o}C and the maximum moisture of 95% and a minimum of 85 % or with an average of 90%. Due to the satisfactory environmental condition of the natural humidifier, it is enabled for the humidifier to guarantee the humidity above 85% according to the controlled settings.

3.2 Effect of natural humidifier operations

The system is equipped with a humidifier system to keep the product moist. The humidifier in this study was developed with a natural system that uses humid outside air that is put into a cooling room with conditioning on a ducting so it is very suitable to be applied in Indonesian villages and no-adequate electricity grid and usually became a center of the horticultural products. So, the analysis of this study focuses on the effect of natural humidifier operation on the operational temperature of the refrigerator which becomes load losses. This analysis is to obtain the best quality and energy efficiency natural humidifier for stored fresh horticultural products. Fig. 6 shows the natural humidifier system that has been developing in this research.

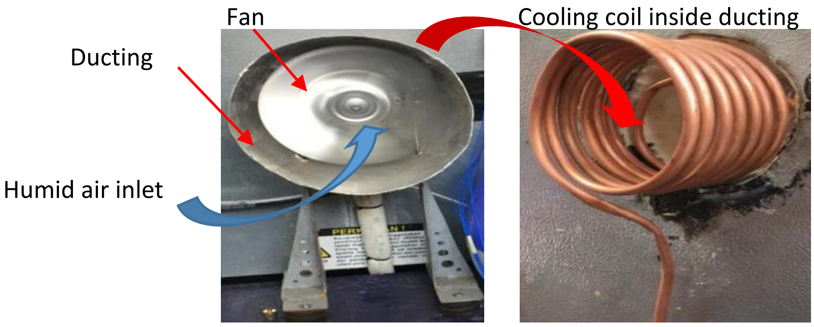


Fig. 6. Natural humidifier test rig.

Investigation of increasing temperature as an effect of the natural humidifier operation was observed. The operation was set with a timer that was operated periodically with the purge charging method. This data is taken only when the compressor is working and the data is not displayed as a whole and data only focus on point 6 (T_6) which refers to Fig.3. The temperature increase profile is shown in the following Fig. 7.

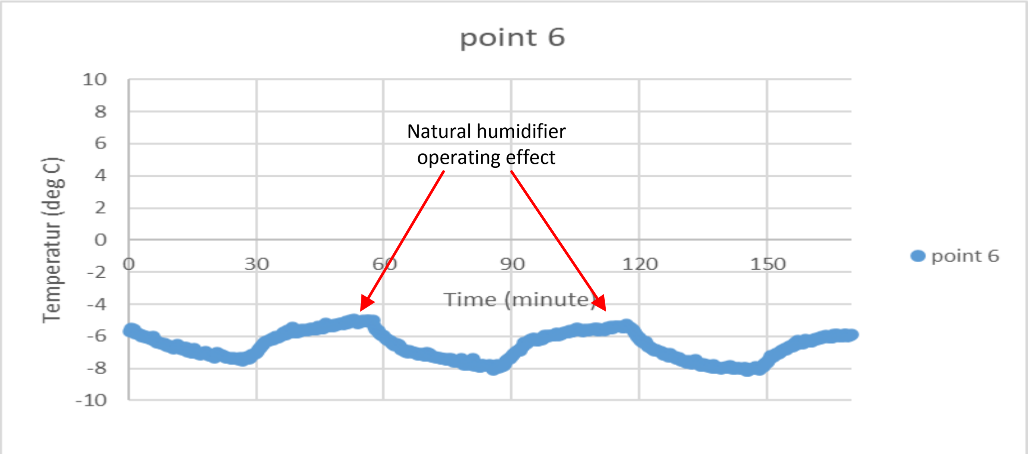


Fig. 7. Temperature increasing on humidifier operating (set at 0°C).

The natural humidifier operation contributes to the temperature increasing at approximately 1 °C -1, 5 °C. It is due to the fresh air purging into the cooling room become a cooling load of both sensible and latent heat. This condition can be solved by the optimized control blower to get the best of amount moisture air to enter the cabin to keep the air humidity. Another urgent improvement of the natural humidifier is the design of the extending evaporator coil (see Fig.6). The extended evaporator coil is not only reducing moist air purging to the cabin but also is intended to guarantee the condition of super-heated refrigerant before entering the compressor.

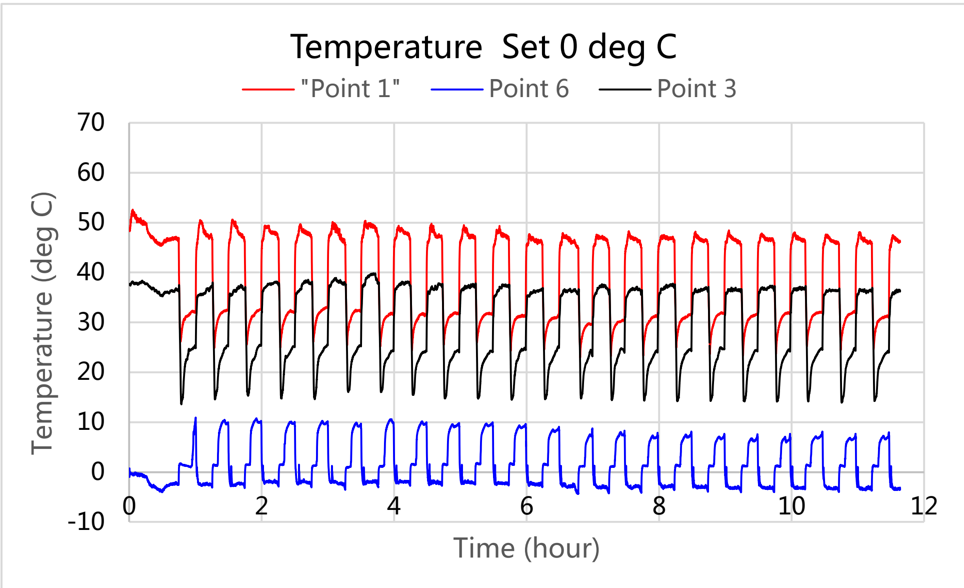
3.3 Refrigerator Performance analysis

Based on the test procedure on the refrigeration cycle system, data collection was carried out on two different variable conditions, temperature setting at 0°C and 5°C and with product load. Solar energy supply during the day and will be switch on nation grid electricity when the solar system is not enough to the refrigeration system. The results of the logger data are shown in Fig. 8 with points from 1 to 6 in the refrigeration system refer to Fig. 3. However, in the graph, only temperature at three main points is shown.

From the data condition, it can be seen that the compressor is working very optimally. Furthermore, the design of a better cooling room will be optimized, especially with better insulation, so that the compressor load will be lower. The performance under these conditions is obtained based on the calculation of the coefficient of performance (COP) thermodynamically with equation as follow:

$$COP = \frac{\dot{m}(h_6 - h_4)}{h_1 - h_6} \tag{1}$$

(a)



(b)

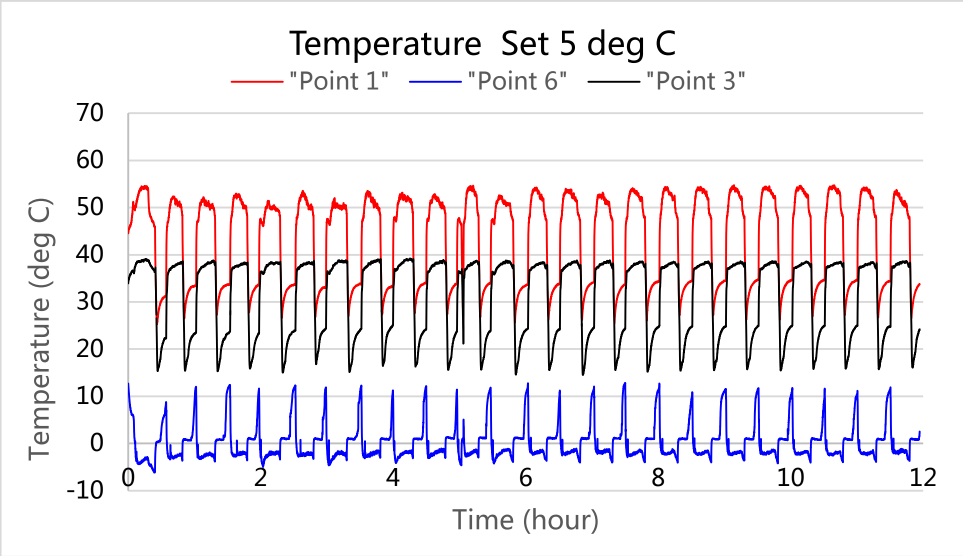


Fig. 8. Average temperature on each point investigated : (a) set at 0°C and (b) set at 5°C.

Where, $h_3 = h_4$ (iso-enthalpy) and mass flow rate is calculating using energy balance approached at the compressor, where energy consumed and compressor work assumed to be equal. This is just to confirm the capacity of the system that is balanced and obviously, further study the mass flow rate of refrigerant in the system will be measured directly. The equation is as follow:

Power input = compressor work

$$V.I = \dot{m}(h_1 - h_6) \quad (2)$$

From equations (1) and (2), it can define the theoretical COP and refrigerant mass flow rate values which set cabin temperature at 0°C and 5°C. the COP and mass flow rate were obtained around 3.6 and 0,0061 kg/s, respectively. From the results of this COP, it can be concluded that the system performance is quite good at these operating temperature conditions. According to these preliminary data, it was found that the prototype refrigerator was working well and the solar power supplier could work continuously during the day. However, because these results are still preliminary, the equipment will be developed with more comprehensive test conditions, by expanding the operating temperature range, refining the control system with analog-digital systems, and developing system optimizations to achieve higher COP.

This experiment will be developed and continued by directly analyzing the energy supply conditions of the solar power system. So that the two systems will be analyzed simultaneously in terms of energy supply and the operating conditions of the refrigerator system. Furthermore, we will be able to compare the efficiency of the system with direct solar power, DC refrigerator system, and refrigerator using solar power with an inverter and refrigerator systems that are still AC-based systems.

3.4 Product quality

The vegetable condition put in the refrigerator is not the best condition, because it is taken from a traditional market that has undergone a lack of quality of cooling previously. This experiment condition is 90% RH and the temperature is 5^{o}C. This preliminary observation shows the capability refrigerator with certain temperature and humidity control was working well under Indonesian ambient temperature conditions. Further study for product quality investigating, the testing will vary from 5^{o}C until 15 ^{o}C with 5^{o}C step and humidity vary from 85% until 95%.

4. Conclusions

This study focused on investigating the operational influence of natural humidifier on the refrigeration cycle performance. The environmental condition is the basis of this system because the humid environment can be a source to add moisture to the moist air environments. The moisture distribution of environmental air can increase the humidity in the cabin. But this also leads to the addition of the load on the cooling system, where there is increased by an average of 1^o C – 1.5 ^{o} C when the humidifier is in operation. The refrigerator system already operates in quate good condition with energy supply from the photovoltaic array. The performance of the refrigeration system was obtained of average thermodynamically COP of 3.6.

Further research will be focused on improving the natural humidifier design to improve the optimization of the refrigeration system, and developing a DC refrigerator system that can run directly using a Photovoltaic array without an inverter. To get a good comparison to be implemented in Indonesian country.

5. Acknowledgment

This research was supported by the Directorate of Research and Community Services (DRPM) - Ministry of Research and Technology-BRIN, Indonesian Government, No. SPKK : 180/SP2H/LT/DRPM/2021 and SP DIPA- 042.06.1.401516/2021 for the in cash contribution. The authors wish to acknowledge the contributions of The Mechanical Engineering Department -Bali State Polytechnic for the in-kind contributions. Also, Centre for Research and Community Service (P3M-PNB) for all administrative support.

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